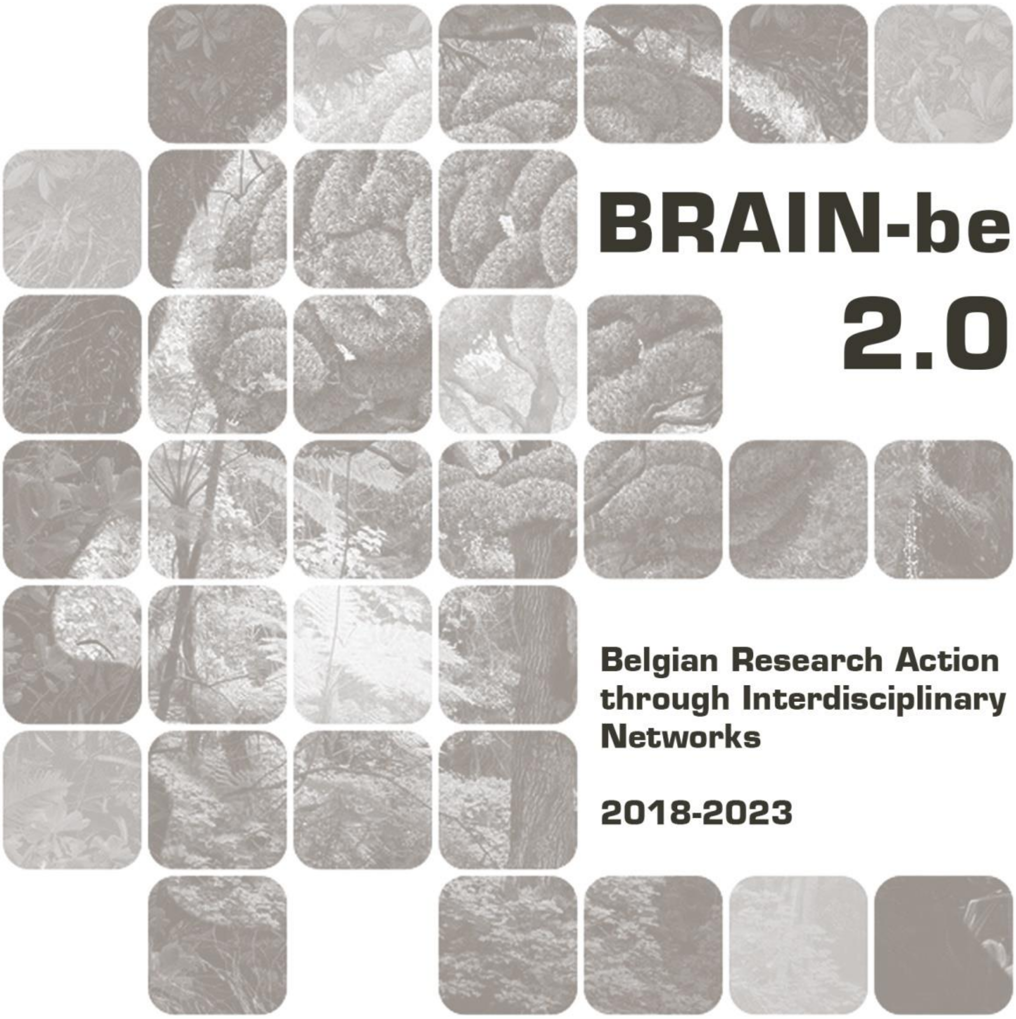

GEOCAMB

GeoCamb

Geothermal Energy Potential in Cambrian rocks focusing on public buildings

ESTELLE PETITCLERC (RBINS) – KOEN VAN NOTEN (ROB) – GUST VAN LYSEBETTEN (BUILDWISE) – JEROEN VAN DER VEKEN (BUILDWISE) – KRISTINE WALRAEVENS (UGENT) – PIERRE GERARD (ULB)

Pillar 1: Challenges and knowledge of the living and non-living world

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NETWORK PROJECT

GeoCamb

Geothermal Energy Potential in Cambrian rocks focusing on public buildings

Contract - B2/191/P1/GEOCAMB

FINAL REPORT

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RÉSUMÉ

Le projet GeoCamb s’inscrit dans un contexte de transition énergétique visant à réduire la dépendance de la Belgique aux combustibles fossiles et à atteindre les objectifs climatiques de l’Union européenne pour 2030. Ces objectifs incluent une augmentation significative de la part des énergies renouvelables, avec un accent particulier sur la décarbonisation du chauffage et du refroidissement, qui représentent 50 % de la consommation énergétique. Dans ce cadre, la géothermie, et en particulier l’utilisation des formations cambriennes du Massif du Brabant, présente un fort potentiel à Bruxelles et ses environs. Cependant, le développement de ces systèmes reste limité par entre autres la complexité géologique, le manque de données sur le socle, et un investissement important.

GeoCamb avait pour objectif principal d’évaluer et de démontrer le potentiel géothermique des roches cambriennes situées sous Bruxelles et les provinces du Brabant. Ce projet visait à caractériser ces formations sur les plans géologique, géophysique et hydrogéologique, tout en évaluant les besoins énergétiques de bâtiments publics susceptibles de bénéficier de ces systèmes. En mobilisant une approche multidisciplinaire, GeoCamb a combiné exploration sous-sol, modélisations 3D, tests hydrogéologiques et analyses des besoins thermiques de bâtiments. En parallèle, le projet s’est concentré sur la collaboration avec des partenaires publics et privés afin d’optimiser l’utilisation des données disponibles et d’étendre les connaissances scientifiques. Une attention particulière a été accordée aux bâtiments publics, qui représentent des opportunités stratégiques pour la démonstration de la géothermie comme source d’énergie durable.

Le projet s’est appuyé sur plusieurs étapes clés. Tout d’abord, une vaste collecte de données existantes a été réalisée. Ces informations ont été consolidées dans une base de données rassemblant 107 forages dans le socle Cambrien et prenant en compte les paramètres utiles pour l’étude du potentiel permettant de mieux comprendre la stratigraphie et la structure du sous-sol. Parallèlement à l'étude géologique, une vaste campagne de bruit sismique a été menée à l'aide de capteurs sismiques mobiles. Celle-ci a permis de mieux cartographier le sommet du Massif du Brabant sous la région de Bruxelles, surtout sous les sites non-explorées à l’aide de forages. Ensuite, une approche participative, appelée « win-win », a permis de collaborer avec des projets en cours pour mutualiser les ressources et les résultats. Parmi les initiatives phares, cinq études de cas ont été menées, comme le bâtiment Paul Henri Spaak (PHS) et le site Gandhi à Molenbeek, afin d’évaluer la faisabilité de systèmes géothermiques. Parallèlement, des modélisations ont été effectuées sur le site de Tour & Taxis pour étudier les interactions potentielles entre systèmes ouverts situés dans des aquifères différents.

Les résultats du projet mettent en évidence un fort potentiel géothermique dans le socle cambrien. Les forages exploratoires, notamment celui de Molenbeek, ont confirmé que la profondeur du socle augmente progressivement du sud vers le nord sous Bruxelles et que le socle présente une conductivité thermique élevée, atteignant 3,8 W/mK dans certaines zones. Les analyses des tests de pompage ont révélé des débits hydrauliques variables, reflétant une fracturation hétérogène du socle. Ces caractéristiques sont favorables à l’implantation de systèmes géothermiques, qu’ils soient fermés (BTES) ou ouverts (ATES). Cependant, les systèmes fermés apparaissent plus adaptés aux environnements urbains denses comme Bruxelles, tandis que les systèmes ouverts conviennent mieux à des projets de plus grande échelle où des aquifères sont accessibles.

Les études de cas ont permis de démontrer l'efficacité de ces technologies. Sur le site Gandhi à Molenbeek, bien que l'étude soit limitée à une préfaisabilité, les résultats fournissent des éléments cruciaux pour envisager un système géothermique dans le cadre d'une rénovation à venir prochainement. Enfin, l'étude d'interférences et les simulations sur le site de Tour & Taxis ont montré que les interactions entre systèmes dans différents aquifères sont limitées, mais que l'équilibre thermique à l'échelle du bâtiment est essentiel pour maintenir l'efficacité à long terme.

En conclusion, le projet GeoCamb souligne le potentiel inexploité du socle cambrien pour la géothermie peu profonde en Belgique. Ses résultats renforcent la nécessité de poursuivre les explorations et d'améliorer la centralisation des données disponibles (hydro-géologiques, thermiques, énergétiques, …) . GeoCamb recommande également une sensibilisation accrue des décideurs publics et des acteurs privés pour encourager le soutien et l'investissement dans ces technologies. Enfin, le projet met en avant l'importance de systèmes pilotes dans les bâtiments publics comme levier pour promouvoir une énergie durable et réduire l'empreinte carbone en Belgique.

Mots-clefs : Géothermie, systèmes ouverts, systèmes fermés, Cambrien, Paléozoïque, Massif de Brabant

ABSTRACT

The GeoCamb project is set within the context of the energy transition aimed at reducing Belgium's dependency on fossil fuels and achieving the European Union's climate objectives for 2030. These objectives include a significant increase in the share of renewable energy, with a particular focus on decarbonizing heating and cooling, which account for 50% of energy consumption. In this framework, geothermal energy, particularly the use of Cambrian formations in the Brabant Massif, offers strong potential. However, the development of such systems remains limited due to among others geological complexity, lack of data on the basement rocks and important upfront costs.

The primary objective of GeoCamb was to assess and demonstrate the geothermal potential of Cambrian rocks beneath Brussels and the Brabant provinces. This project aimed to characterize these formations from geological, geophysical, and hydrogeological perspectives while evaluating the energy needs of public buildings that could benefit from these systems. By employing a multidisciplinary approach, GeoCamb combined subsurface exploration, 3D modelling, hydrogeological testing, and the analysis of the thermal demand profiles of buildings. Concurrently, the project focused on collaboration with public and private partners to optimize the use of available data and expand scientific knowledge. Special attention was given to public buildings, which represent strategic opportunities for demonstrating geothermal energy as a sustainable energy source.

The project followed several key phases. First, an extensive collection of existing data was carried out. This information was consolidated into a database that gathered a total of 107 boreholes in the Cambrian bedrock. In parallel with the geological survey, an extensive seismic noise campaign was conducted using seismic nodal sensors. This allowed to better map the top of the Brabant Massif below Brussels region, especially under sites where the bedrock was unexplored by drillings. Next, a participatory "win-win" approach enabled collaboration with ongoing projects to pool resources and results. Among the flagship initiatives, five case studies were conducted, such as the Paul Henri Spaak (PHS) building and the Gandhi site in Molenbeek, to assess the feasibility of geothermal systems. Parallel to these efforts, modelling studies were performed at the Tour & Taxis site to examine potential interactions between open systems located in different aquifers.

The project's results highlighted the strong geothermal potential of the Cambrian basement. Exploratory boreholes, including the one at Molenbeek, confirmed that the basement depth gradually increases from south to north below Brussels and that the basement rock exhibits a high thermal conductivity, reaching 3.8 W/mK in some areas. Analyses of pumping tests revealed variable hydraulic flows, reflecting heterogeneous fracturing of the basement. These characteristics are favorable for implementing geothermal systems, whether closed-loop (BTES) or open-loop (ATES). However, closed-loop systems appear to be better suited to dense urban environments like Brussels, while open-loop systems are more appropriate for larger-scale projects where accessible aquifers are available.

The case studies demonstrated the effectiveness of these technologies. At the Gandhi site in Molenbeek, although the study was limited to a pre-feasibility assessment, the results provided crucial insights for considering a geothermal system as part of future renovations. Finally, an impact study and simulations at Tour & Taxis showed limited interactions between systems in different aquifers but emphasized that thermal balance at the building level is essential to maintain long-term efficiency.

In conclusion, the GeoCamb project underscores the untapped potential of the Cambrian basement for shallow geothermal energy in Belgium. Its findings highlight the need for continued exploration and an enhanced, centralized database of geothermal project parameters (hydro-geological, thermal, energetical, …). GeoCamb also advocates for increased awareness among policymakers and private actors to encourage support and investment in these technologies. Lastly, the project emphasizes the importance of pilot systems in public buildings as a lever to promote sustainable energy and reduce Belgium's carbon footprint.

Keywords: Geothermal energy, open systems, closed systems, Cambrian, Paleozoic, Brabant Massif

SAMENVATTING

Het GeoCamb-project kadert in de energietransitie die België minder afhankelijk moet maken van fossiele brandstoffen en de klimaatdoelstellingen van de Europese Unie voor 2030 moet halen. Deze doelstellingen omvatten een aanzienlijke verhoging van het aandeel van hernieuwbare energie, met een bijzondere focus op het koolstofvrij maken van verwarming en koeling, die 50% van het energieverbruik uitmaken. In dit kader biedt geothermische energie, en meer specifiek het gebruik van de Cambriumformaties in het Brabant Massief, een groot potentieel. De ontwikkeling van geothermische systemen in deze formaties blijft echter beperkt door onder andere de geologische complexiteit, een gebrek aan gegevens over het sokkelgesteente en de hoge aanvangskosten.

Het hoofddoel van GeoCamb was het beoordelen en aantonen van het geothermische potentieel van de Cambriumgesteenten onder Brussel en de Brabantse provincies. Het doel van dit project was om deze formaties te karakteriseren vanuit geologisch, geofysisch en hydrogeologisch perspectief en tegelijk de energiebehoeften te evalueren van openbare gebouwen die van deze systemen zouden kunnen profiteren. Door gebruik te maken van een multidisciplinaire aanpak combineerde GeoCamb exploratie van de ondergrond, 3D-modellering, hydrogeologische tests en analyses van de thermische behoefteprofielen van gebouwen. Tegelijkertijd richtte het project zich op samenwerking met publieke en private partners om het gebruik van beschikbare gegevens te optimaliseren en wetenschappelijke kennis uit te breiden. Er werd speciale aandacht besteed aan openbare gebouwen,

die strategische mogelijkheden bieden voor het demonstreren van geothermische energie als duurzame energiebron.

Het project volgde verschillende belangrijke fasen. Eerst werden bestaande gegevens uitgebreid verzameld. Deze informatie werd geconsolideerd in een database die in totaal 107 boorgaten in het Cambrium bevatte. Parallel met het geologisch onderzoek, werd een uitgebreide seismische ruis campagne uitgevoerd met behulp van seismische sensoren. Deze campagne liet toe om de top van het Brabant Massief onder Brussel en omstreken beter in kaart te brengen, vooral daar waar de diepte niet was gekend door boringen.

Vervolgens maakte een participatieve “win-win”-benadering samenwerking met lopende projecten mogelijk om middelen en resultaten te bundelen. Als vlagschipinitiatief werden vijf casestudies uitgevoerd, zoals het Paul Henri Spaak (PHS) gebouw en de Gandhi site in Molenbeek, om de haalbaarheid van geothermische systemen te beoordelen. Parallel met deze inspanningen werden modelstudies uitgevoerd op de site van Tour & Taxis om de mogelijke interacties tussen nabijgelegen open systemen in verschillende watervoerende lagen te onderzoeken.

De resultaten van het project benadrukten het sterke geothermische potentieel van de Cambrische sokkel. Verkennende boringen, waaronder die in Molenbeek, en geofysische metingen bevestigden dat de sokkeldiepte geleidelijk toeneemt van zuid naar noord onder Brussel en dat het gesteente een hoge thermische geleidbaarheid heeft, tot 3,8 W/mK in sommige gebieden. Analyses van pompproeven toonden variabele hydraulische stromingen aan, wat wijst op het heterogene fracturatie van de sokkel. Deze kenmerken zijn gunstig voor de implementatie van geothermische systemen, zowel gesloten systemen (BTES) als open systemen (ATES). Gesloten-lussystemen lijken echter beter geschikt voor dichtbevolkte stedelijke omgevingen zoals Brussel, terwijl open-lussystemen geschikter zijn voor grootschaligere projecten waar toegankelijke aquifers beschikbaar zijn.

De casestudies toonden de doeltreffendheid van deze technologieën aan. Hoewel de studie op de Gandhi-site in Molenbeek beperkt was tot een voorafgaande haalbaarheidsstudie, leverden de resultaten cruciale inzichten op voor het overwegen van een geothermisch systeem als onderdeel van toekomstige renovaties. Tot slot toonden de impactstudies en simulaties bij Tour & Taxis slechts beperkte interacties aan tussen systemen in verschillende aquifers, maar ze benadrukten dat thermisch evenwicht op gebouwniveau essentieel is om de efficiëntie op lange termijn te verzekeren.

Tot besluit bevestigt het GeoCamb-project het onaangeboorde potentieel van de sokkel voor ondiepe geothermische energie in België. De resultaten benadrukken de nood aan verder onderzoek en een betere gecentraliseerde databank voor alle relevante parameters (hydro-geologisch, thermisch, energetisch, …). GeoCamb pleit ook voor een groter bewustzijn bij beleidsmakers en privéactoren om steun en investeringen in deze technologieën aan te moedigen. Tot slot benadrukt het project het belang van pilootprojecten in openbare gebouwen als hefboom om duurzame energie te promoten en de koolstofvoetafdruk van België te verminderen.

Trefwoorden: Geothermische energie, open systemen, gesloten systemen, Cambrium, Paleozoïcum, Brabantmassief

1. INTRODUCTION

While the EU is on track to meet its goal of 20% renewable energy production in 2020, the new 2030 target has been set at **at least 42.5%** renewable energy share in final energy consumption, with an additional indicative target of reaching **45%** under optimal conditions (European Commission, 2023). For Belgium, the binding national contribution aligns with the EU's climate goals, aiming for a significant increase in renewable energy, though challenges persist due to the country's high reliance on imported energy and its limited progress in certain sectors.

To achieve the renewable energy share in the total energy use in Belgium, geothermal energy can play a substantial role in the heating sector, which accounts for **approximately 50%** of total energy use. Both shallow and deep geothermal have potential to contribute to this energy share. In Belgium, shallow geothermal energy (SGE) use for heating, cooling, and seasonal storage has the potential to become a key instrument for reducing the dependency on energy imports and lowering emissions by enhancing the decarbonisation of the heating and cooling market.

Although 2/3 of the total installed capacities and more than 85% of all investments in the European geothermal sector are related to SGE use (European Geothermal Energy Council, Market Report 2015, fifth edition April 2016), these simple and very adaptable heating and cooling techniques still suffer from a lack of visibility and awareness among the general public. After a period of stagnation in the development of shallow geothermal energy systems in Belgium between 2014 and 2017, a significant revival has been observed. In 2021, the sales of Ground Source Heat Pumps (GSHP) in Belgium increased by 35%, reflecting a growing interest in these technologies (cf. egec.org). Although precise data on the total number of installations and overall capacity are not available, this trend suggests increased adoption of GSHP, supported by research initiatives and pilot projects aimed at promoting geothermal energy use in Belgium

Belgian research projects in shallow geothermal energy (e.g., ThermoMap, SmartGeotherm, Brugeo, RegeoCities, GeotherWall, BeTemper, Muse (GeoEra), GeoWal), financed by regional, federal, and European initiatives, played a significant role in that development. Brugeo and SmartGeotherm focused on geothermal potential mapping of the Flemish and Brussels regions and developed web applications to guide project developers and citizens by providing underground parameters. However, the Brabant Massif bedrock potential was mainly not considered due to insufficient data.

The geological composition of the subsurface under the Brabant and Brussels regions is characterized by two major tectonosedimentary units, namely a Meso-Cenozoic sedimentary cover (well-known and currently mainly used for shallow geothermal purposes) and the deformed Lower Palaeozoic meta-sedimentary layers of the Brabant Massif (i.e. the basement and only punctually known). The Brabant Massif was intensely folded during the Brabantian deformation event, while the Meso-Cenozoic cover is only slightly tilted towards the North-East due to uplift. Although the Brabant Massif is largely concealed under its cover, its reconnaissance on Belgian territory resulted from series of deep boreholes, outcrop studies along incised river valleys South of Brussels and geophysical data (Bouguer, aeromagnetic). The global structure of the Brabant Massif corresponds to a WNW-ESE oriented tectonic belt with Cambrian meta-sedimentary formations in its centre and Ordovician and Silurian units along the edges. The structural grain of the Brabant Massif was mapped by means of boreholes and outcrop studies at regional scale (Figure 1).

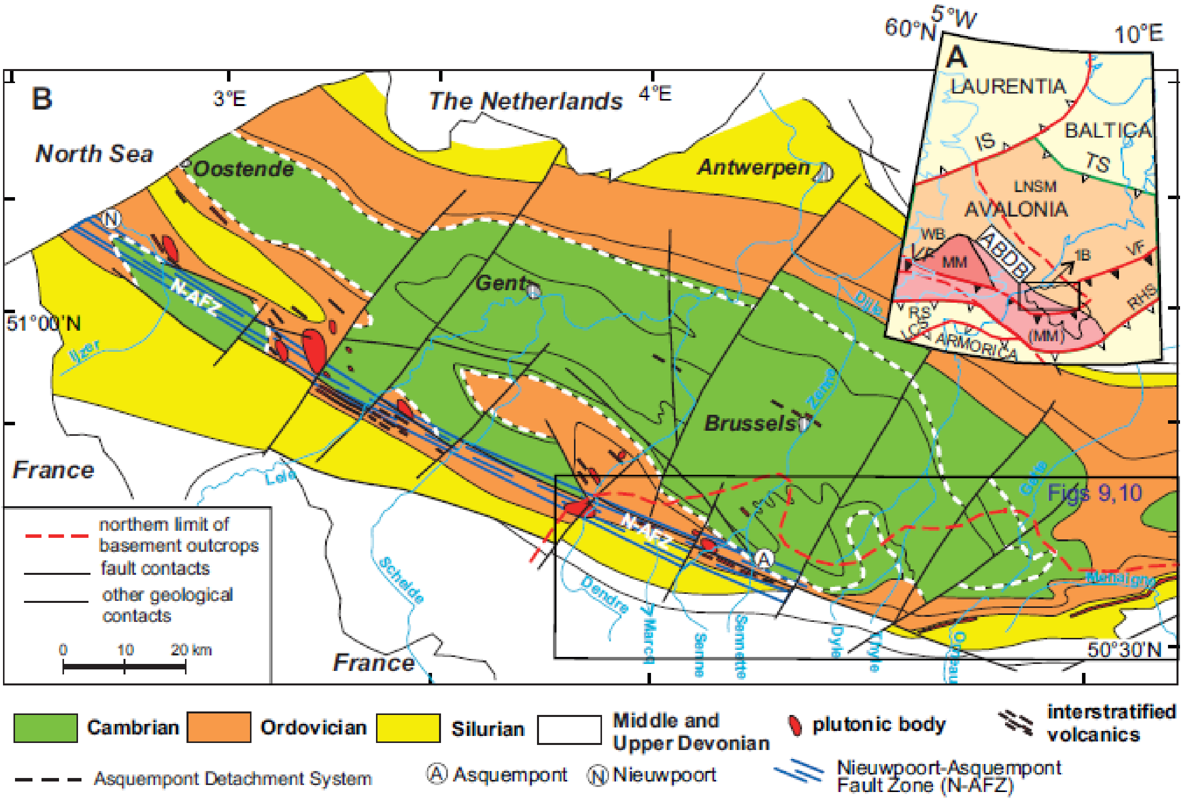


Figure 1 Geological subcrop map of the Brabant Massif.(Herbosch & Debacker, 2018)

Below Brussels, the Cambrian Tubize (TUB) and Blanmont (BLM) formations are present. TUB is magnetic and consists of alternation of shales, sandstones, quartzites, often organised in turbiditic sequences, while the BLM is non-magnetic and predominantly consists of quartzites, sometimes alternated with shales. As the Brabant Massif is intensely folded and Brussels is located above the core of the Brabant Massif, geophysical data and boreholes confirm the mostly upright position of the beds below Brussels.

On the scale of a potential geothermal borehole, alternation of beds, lithology, stratigraphy, permeability, depth and fracturing are unknown or have a large uncertainty, even though the basement is relatively close to the surface along the southern part of the Brabant Massif (see Figure 1Figure 2, in outcrop in the Tubize area, from ~30 m depth in the Brussels Senne valley to 300 m depth north of Brussels).

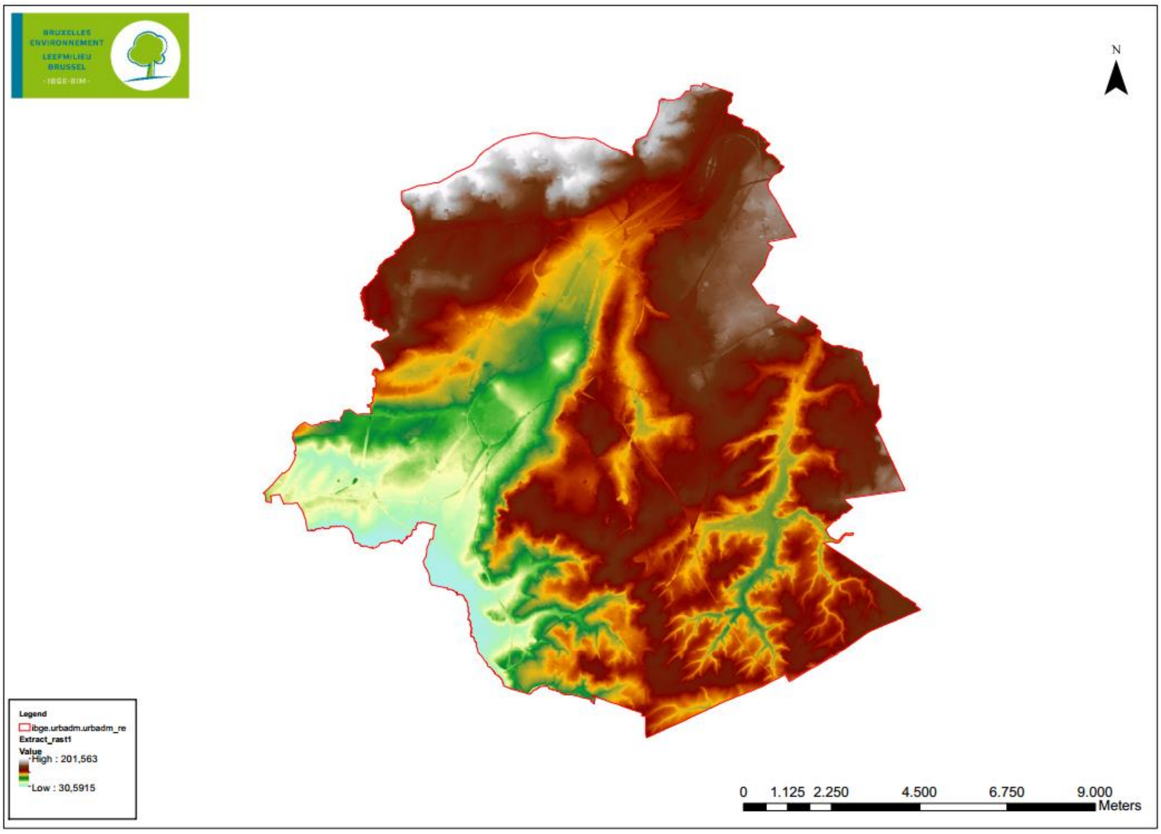


Figure 2 Top of the Paleozoic (Cambrian) of the Brussels region (derived from Brustrati3D model from 2018)

This lack of information induces geothermal project developers and contractors to prefer low-efficient geothermal systems in the Meso-Cenozoic cover (sand and clay) rather than taking high financial risks due to geological uncertainties in the Brabant Massif (folded and faulted rocks). Indeed, with the previous knowledge of the Palaeozoic basement, geothermal systems remained rather random despite the positive results of the recent exploration drilling at Anderlecht (extensive flow rate, high thermal properties highlighted in the Brugeo project) and the Gare Maritime pilot-project (i.e. a cover town at Tour & Taxis in Brussels, with 10 wells in Cambrian rock; the installation will provide 1396 kW to cover the whole heating/cooling needs of the 45,000 m^2).

The geothermal survey at Anderlecht demonstrated punctually the high potential for open and closed loops geothermal systems in the Cambrian core of the Brabant Massif. A more extensive use of the Cambrian bedrock (including at greater depths) is ongoing now in 2024 to cover important public building energy needs and to enhance geothermal sector development in the Brabant and Brussels territories. Due to more requiring or zero energy buildings norms, more and more public building renovations or constructions resort to a mix of renewable energies among which geothermal energy brings usually a small part of heating/cooling needs (e.g. Delta Hospital, Administrative city hall of Etterbeek, Brussels Environment building, EU buildings at Brussels). In 2020, most of these geothermal systems were traditionally installed in the Meso-Cenozoic cover, while a closed or open geothermal system in the bedrock might have a much larger potential and might be more efficient.

2. STATE OF THE ART AND OBJECTIVES

2.1. Objectives

The main objective of the GeoCamb proposal was to evaluate and demonstrate the geothermal potential of the Cambrian bedrock, from surface demand to the subsurface, subcropping beneath the Flemish/Walloon Brabant provinces and in Brussels region. The depth of the Palaeozoic bedrock in those areas (from 0 to 300 m) is adequate for the installation of both open and closed loop geothermal systems.

GeoCamb's scope focused on geological, geophysical and hydrogeological exploration in Brussels and both Brabant provinces to identify the bedrock and better understand the underground potential. In parallel, the potential geothermal needs of several existing buildings were evaluated in 5 case studies where underground exploration was set up for 2 of them. Finally, the economic and environmental impact of geothermal energy exploration/use in densely populated areas was addressed to promote a sustainable use of the resources. The GeoCamb consortium composed of 2 federal institutes (GSB, ROB), three universities (UGent-LTGH, ULB, and ULG as sub-contractor), one research institute (BUILDWISE) and one private firm (Artesia, sub-contractor) represented a valuable multi-disciplinary team to achieve these objectives.

2.2. State of the art

The research environment / fields: GeoCamb aimed to go further and deeper than previous Belgian geothermal projects by developing in parallel the assessment of regional heat demand (surface needs) and specific underground geothermal potential which are relevant for a complex reservoir such as the Brabant Massif. Unlocking potentials of further innovation was supported by interactive cooperation in workshops and by the specific work performed in the 2 pilot case studies and at the Tour et Taxis survey. A win-win approach was developed thanks to close contacts of the consortium with designers, drillers and installers and was set up with existing or on-going private/public geothermal installations/projects allowing more scientific data and analyses than in a single exploration way.

Use of the subsurface: In a world where local resources are getting scarcer, a better planning and use of the subsurface, in terms of water resources, energy applications and storage opportunities, will prove to be beneficial for the whole society in the long term. The project also investigated interferences at local level and their influence on environment and performance (Tour & Taxis survey). Ultimately this should allow for a better direction of research efforts and public support.

Non-invasive methodologies: GeoCamb aimed to use non-invasive geophysical methods with seismometers and geophones to study geological contrasts in the subsurface using state-of-the-art techniques. Gaining expertise in handling these instruments, developing open-source scripts to convert and analyse seismic data linked to underground studies are beneficial for both the general and the scientific community. The depth of the Brabant Massif is only known from borehole data and geophysical data will help to better model this geothermal 'reservoir'. From these initiatives, seismic velocity of the subsurface can be derived. On the long term, any risk associated with geothermal energy (e.g. microseismicity) will benefit from having an accurate cover and bedrock velocity model and improve seismic wave arrival picking. Evaluating the influence of site effects (induced by soft sediments above the Brabant Massif) on (past) earthquake ground motions is valuable to precise the Eurocode 8 zonation and to improve the quality of ground motion prediction equations, the core of seismic hazard assessment.

Relationship with previous and ongoing regional and EU projects: GeoCamb aimed at sharing and pooling existing knowledge from previous regional and European projects (e.g. SmartGeotherm, Brugeo, MUSE, GeoPlasma-CE, Greta). The link with ongoing EU geothermal research, exchange on best practices, new developments transfer was done (Geo4civhic, GeoEnvi, Geofit, Geothermica…) thanks to the European network of the consortium (EGEC memberships, Eurogeosurveys, European Federation of Geologist, RHC Platform, EHPA, and various research centres and universities contacts). GeoCamb specially benefited and contributed to MUSE project outputs at the early stage of the project (strategies for managing SGE use in cities, catalogue of EU joint methods and workflows for local-scale assessment of resources and possible conflicts related to shallow geothermal energy in cities).

Public buildings: GeoCamb evaluated the ability of the RBINS buildings to be heated/cooled by geothermal energy in a near future in strong collaboration with the renovation project of the neighbouring Paul Henry Spaak building. This case-study represents a unique opportunity for RBINS to assess the potential reconversion from fossil fuel to a renewable energy source and to drastically decrease his energy budget. Priority was be given to public buildings as case-studies and win-win cases all along the project (EU buildings at Brussels, FSIs, Gandhi towers (Logement Molenbeekois)).

Society: The availability of secure and sustainable energy is of high importance to society. Our own subsurface can provide us with energy that is renewable, climate-friendly and domestically produced. Moreover, compared to most other renewables, geothermal energy is continuously available and can thus provide a base load, similar to fossil fuels. Thus, it contributes to a reduction of our carbon footprint and of our dependency on imported fossil fuels. By providing a better knowledge of the Brabant Massif and by demonstrating the efficiency of geothermal systems, this helped reducing investment risk allowing better planning of subsurface resources at policy level, with benefits to investors, energy companies, and in the end lead to a more secure, carbon-lean and affordable energy price to the end-users.

Policy-making / Climate and energy: At policy level, energy is a challenging topic because there are many actors and the stakes are high. Climate, energy price, policy support and many other factors need to be balanced. The project contributed to enhance the awareness of geothermal energy to policy makers, citizens and the scientific community.

3. METHODOLOGY

3.1. General approach

To assess and demonstrate the surface and subsurface geothermal potential of the Palaeozoic (mainly Cambrian) basement in the Brussels region and the Brabant provinces, a well-structured and robust multidisciplinary approach was applied by combining subsurface exploration, geophysical surveys, the long-term performance and investigate energy efficiency and needs also for specific case studies in public buildings. During GeoCamb, four investigation means/methods were followed involving the main aspects: 1) Collection and analysis of existing data; 2) The win-win approach; 3) five case studies; 4) one interference test site at Tour & Taxis.

a) **Collection and analysis of existing data:** Relevant Brabant Massif geological, hydrogeological, thermal data, exploitation data were gathered and analysed from existing drillings, piezometers, pumping wells, geothermal installations in the studied area. Previous geophysical surveys (mainly in Brussels and Walloon Brabant) and well logging data (e.g. Gare Maritime at Tour & Taxis) were collected and reinterpreted. A database was created including the following parameters and information: lithology, drilling parameters, depth to top of the weathered Cambrian, depth to top un-weathered Cambrian, hydrogeological data, temperature data.

b) **Win-win approach**: To get as much information as possible, GeoCamb followed a win-win approach, involving any private or public geothermal project operating in the study area. The idea was to address companies and public organizations that are investigating the Cambrian bedrock and propose them to perform extra tests, analyses and monitoring, to increase the scientific knowledge and in some case help to design installations more accurately. In that way, the GeoCamb team had access to the site and data (underground and surface data), while they benefit from GeoCamb expertise and results. Collection of fresh lithological samples and implementation of geophysical loggings and passive methods, pumping-tests, thermal response tests, and deepening of boreholes in the process of development were considered on a case-by-case basis depending on the time and technical possibilities. Numerous geothermal feasibility studies took place (Etterbeek, Leuven, Louvain-La-Neuve, Swift project at La Hulpe, Kanal Project, KULeuven, etc.) and were selected according to the scientific relevance for GeoCamb. Water-level monitoring was mainly performed at Tour & Taxis site (Gare Maritime, Brussels Environment buildings) and Anderlecht piezometer. Finally, the win-win approach was also applied by ULB and BUILDWISE for economic evaluation and monitoring of existing systems. Operational, exploitation, existing monitoring data and costs of closed systems, whether or not installed in the Cambrian basement were analyzed to evaluate the efficiency of the installations and their long-term performance. Some of them were selected for monitoring (e.g. EU Wilfried Martens, Gare Maritime, Waterloo, U-Square ULB sites, private houses) according to technical feasibility and geological context.

c) **Case-studies in public buildings**: In order to assess the potential of (large) geothermal sources, five different cases were selected. Given the necessary scale and the challenges for renovation and decarbonisation in and around Brussels, three large and two smaller public buildings were studied. Thanks to the highly qualified multidisciplinary team of GeoCamb, this assessment allowed innovative research to better understand the nature, structure and the technical geothermal potential of these local sites and the Brabant Massif in general. The assessments will comprise an energy audit and determination of future heating and cooling needs of the buildings (BUILDWISE WP5), a geological study, hydrogeology (UGent-LTGH) and geophysical investigations (ROB, UGent-LTGH). Since a good knowledge about the buildings and a good cooperation with the building owner is paramount, the sites will be selected in collaboration with the 'Building management office' (FR: *Régie des bâtiments*). However, other public buildings like federal, regional and municipality buildings were also targeted, such as the BUILDWISE new building at Zaventem, Flemish Region building at Brussels, U-Square project for ULB, municipality of Villers-la-Ville and Genappe, etc. One of the large cases was the RBINS case-study which collaborated and complemented the geothermal survey launched by the EU commission in July 2019 for the whole renovation of the neighboring Paul Henri Spaak (PHS) building. In that scope, 4 piezometers were drilled till 300m depth by EU Parliament near the RBINS building. GeoCamb investigated further the underground potential (geological interpretation, two enhanced Thermal Response Tests (e-TRTs), geophysical loggings and surveys, temperature monitoring). BUILDWISE determined how and which RBINS building sections can benefit from the extra heat of the PHS building.

d) **The Tour & Taxis interferences test-site** was originally composed in 2019 of two public buildings equipped by open geothermal systems in the Meso-Cenozoic (Landenian) aquifer (Brussels Environment and Flemish Region buildings) and the Gare Maritime cover town which is currently the first large open geothermal project in the Cambrian basement (10 wells at a depth of 150-200m). This unique site, where main data are made available for the GeoCamb partners and where the active support from the regional authority exists, led to implement further investigations by Artesia and ULG (sub-contractors) with hydrogeological modelling to study interferences between the systems and potential communication between aquifers. An extension of the study was realized in 2024 by ULG, including the 2 planned open systems in the Cambrian basement (Hotel des Douanes and Lake Side)

3.2. Subsoil investigation

In the Brussels region and in its immediate surroundings the geological information on the Cambrian bedrock is rather poor. A few hundreds of bedrock boreholes have been drilled in and around the Brussels' capital region. The 3D geological model of Brussels (Datastore Brussels) is based on 668 boreholes in the Brabant Massif, with ~300 in or closely around the Brussels' Capital region. From that amount, only ~10 wells drilled in the bedrock are used for geothermal purposes and only five open geothermal systems existed (with one in the Cambrian bedrock) at the early stage of the project. In GeoCamb, it was necessary to dedicate a specific exploration budget to conduct **new drilling and tests** (2 case-studies and more than 20 win-win sites). The RBINS-GSB supervised and coordinated the scientific work as well as the administrative work linked to the drilling (permitting, offers, tender...) in the case-studies and extra tests in the win-win approach. The experience gained by the GSB team in geological exploration the last years allowed to properly conduct and coordinated this phase. The selection of suitable exploration sites was decided by the GeoCamb consortium. One GeoCamb exploration drilling (that could be converted in geothermal well) was achieved in Molenbeek Gandhi site and provided direct information on Cambrian depth, lithology, structure, fracturation and alteration. Samples collected were properly characterized regarding their content and their natural variability and physical properties with the analytical RBINS-GSB laboratory equipments.

Hydrogeological parameters are crucial to allow performing open geothermal systems and may create interferences in closed system performance. Past studies demonstrated already a complex hydrogeological behaviour of the Paleozoic basement (e.g. Gare Maritime, Woluwe shopping center, Bois de la Cambre, Anderlecht where various aquifer flow rates were observed from <10m^3/h to 150m^3/h).
UGent-LTGH collected old well completion reports (82 wells) from previous projects and calculated Specific well Capacity (SC), which is a firsthand proxy for hydraulic transmissivity. SC is a simple parameter that can easily be obtained for pumped wells if the pumping rate and drawdown are known. The value of SC is related to the transmissivity, but the relationship is dependent on the lithology of the rock or sediments (Al Farrah et al., 2013). Furthermore, among the 107 GeoCamb win-win test-sites and case studies wells, transmissivity values estimated at 29 wells (mostly in the Brussels Brabant) were complied.
Interpretation of pumping tests has been done using the classical methods of pumping test interpretation assuming radial flow towards the pumping well. It has been observed that pumping wells in fractured rocks often do not agree with the radial flow assumption of most classical interpretation methods. An innovative approach is therefore to use the solution of Barker (Barker, 1988), developed based on the concept of fractional dimension, to fit the data and obtain hydraulic parameters. A software tool, based on the analytical solution of Barker (1988), was developed for the interpretation of pumping tests that uses the concept of fractional flow dimension, by the study team. The solution extends the classical Theis solution to fractional flow dimensions (n), ranging from 1 to 3, representing linear, radial, and spherical flow, respectively. In other words, it incorporates flow dimensions (n) as a fractional value based on the geometry of flow. The developed computational program is used to interpret the time-drawdown data from pumping tests by fitting the observed data to the Barker model i.e. calibrating the flow dimension (n) to match the observed pressure response. The tool uses a Monte Carlo random sampling strategy of the model parameters as an optimization routine. It was applied with the pumping test data of Anderlecht well and latter for Molenbeek case study well. The first phase of the step drawdown pumping test can be considered as a constant pumping test type, and hence, the transmissivity has been estimated by the tool.

Furthermore, time series piezometric level data of 12 wells in the Cambrian aquifer, mostly located in west Flanders, obtained from VMM (DOV portal) were interpreted. For most of the monitoring wells, the data recoding had started in early 2000s while on some wells, it was being recorded since 1990s. Those hydrographs were interpreted to see how historically the water level is evolving especially in response to exploitation.

To better understand the sediment and bedrock nature, borehole logging equipment (from UGent-LTGH) was used. Methods used to deduce sediment composition, stratigraphy, aquifer geometry and information related to hydraulic parameters and to groundwater composition include measuring the caliper of the well, natural gamma radiation, temperature, resistivity (LN and SN), single point resistance, lateral resistivity, spontaneous potential, fluid resistivity and electromagnetic induction. In open or PVC cased wells the conductivity and converted resistivity can be logged with a slim hole induction tool. A video camera logging tool will be hired to understand fracturation and its hydraulic role.

In order to determine the **soil thermal conductivity**, the (undisturbed) soil temperature and the thermal gradient, five e-TRTs were performed by BUILDWISE. For a Thermal Response Test (TRT), a borehole with closed loop heat exchanger is required, while an e-TRT requires the installation of a hybrid cable (heating cable + fibre optic temperature sensing cable) in the borehole (might be a geothermal well, a piezometer or another borehole). BUILDWISE owns the devices to perform these tests, whereas the optic fibre was acquired (length of 2000m) as well as a generator was rented to provide continuous power supply during the whole test duration (around 15 days typically to account for a heating and cooling phase). The thermal properties measurements on cores samples of Molenbeek drilling and from RBINS-GSB core-collection were performed at GSB laboratory using optical scanning method (Thermal Conductivity Scanner) which provides high precision, non-destructive thermal conductivity and diffusivity measurements (Popov et al., 1999, 2012).

Passive seismic geophysical methods were applied by the ROB to study the geological structure around the studied boreholes. We relied on state-of-the art site characterization methodologies (i.e. methods to characterize the geology below a seismic sensor) to deduce shear-wave velocity (Vs) profiles from passive seismic array measurements (seismometers placed in a geometrical configuration measuring the ambient noise). Horizontal/Vertical (H/V) spectral ratio analyses of ambient noise measurements around pre-selected boreholes were applied to determine the soil’s resonance frequency (f0) and to convert f0 to depth using conversion equations designed for Brussels (Van Noten et al., 2022). H/V analysis turned out to be a key technique to provide additional data to better model the depth to bedrock below Brussels and to include that in public 3D models. From earlier projects (Belspo EPOS.BE project), the ROB had already experience in using 24 IGU-16HR 3C (3-component) SmartSolo 5 Hz seismic nodes. During GeoCamb, 10 additional 3C nodes and seven 5s IGU-BD3C-5 5s seismic nodes were bought. With this instrumentation, the ROB improved its expertise in instrument installation, data conversion and seismic and geophysical data analysis (using Geopsy, open python scripts).

3.3. Energy performance and impact of running systems and building energy demand

The monitoring of existing geothermal systems consists of the following actions performed conjointly between ULB and BUILDWISE: 1) Identification of possible open and closed geothermal systems that can be monitored (EU Wilfried Martens, Gare Maritime, Waterloo buildings, U-Square ULB building); 2) Installation of monitoring systems and sensors; 3) Collection of data and analysis in order to assess/demonstrate the long-term performance and the sustainability of the geothermal systems, with a specific focus on the impact of Cambrian basement on the efficiency of the system; 4) Comparison of monitoring data with analytical solutions already developed at ULB and predicting the temperature field around ground heat exchangers for discontinuous heat extraction and heterogeneous geological and hydrogeological conditions; 5) Improvement of analytical solutions based on monitoring data in order to propose sustainable and efficient design solutions for such systems. For some projects, the temperature evolution in the closed loop probes of a geothermal field was monitored with optical fibers. In combination with the energy flows between building and soil, this provides very valuable information for modelling and understanding of what happens in the subsoil.

Based on literature review, the Cambrian environmental risks assessment for open geothermal projects including thermal and radioactive pollution, subsidence (Declercq, 2017), and groundwater contaminations helped to determine preliminary recommendations to these problems.

The assessment of the building energy demand and boundary conditions in WP5 (BUILDWISE) starts with a data collection process in close cooperation with building owners. Only very limited additional test equipment was installed during the project (such as energy meters, temperature sensors, etc.), as integrating them into existing buildings and systems proved to be rather complex. After the building audit, the suitability of the building and the current heat emitters was assessed in relation to the future geothermal system. Renovation measures (including the building envelope) are often required to lower the necessary heating (or cooling) power and increase the resulting comfort in relation with the limited heating (cooling) power that can be emitted at interesting regime temperatures. In cooperation with the building owners, feasible renovation packages were composed and put in a dynamic building energy simulation environment (TRNSYS or Design Builder) so that the future heating and cooling needs could be calculated. The resulting heat and cold demand curves were used together with the previously defined soil thermal parameters in WP2 and WP3 to run the geothermal design simulations (e.g. Earth Energy Designer) and determine the necessary geothermal source length, type and costs.

4. SCIENTIFIC RESULTS

4.1. Methodological advances

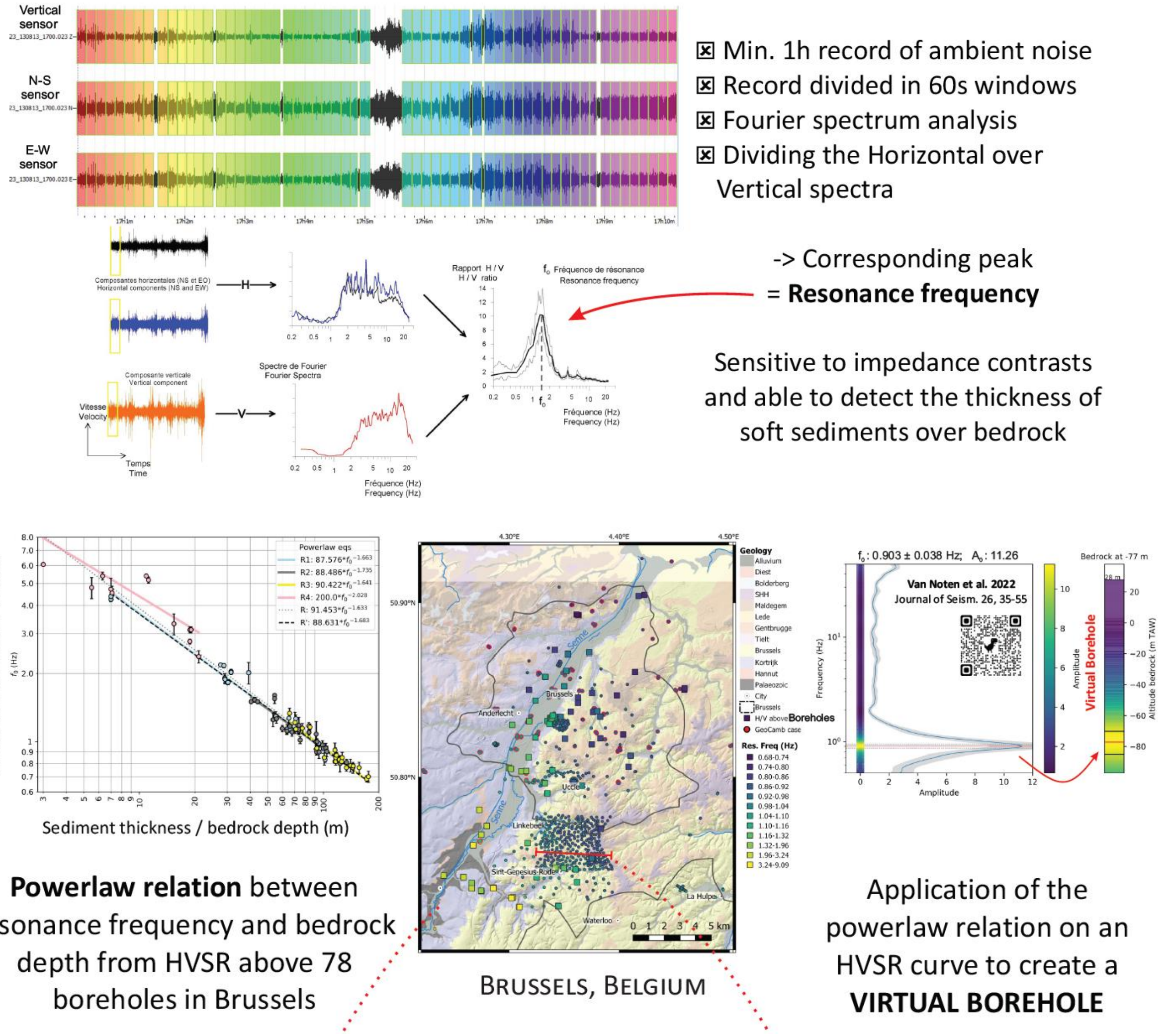
The GeoCamb project was a multidisciplinary project in which numerous different techniques were applied. Several techniques were significantly improved in the course of this project.

4.1.1 Horizontal/Vertical spectral ratio analysis of ambient noise

The 1-D Horizontal-to-Vertical Spectral Ratio (HVSR) analysis of ambient seismic noise is a widely-applied, non-invasive technique often used to determine the resonance frequency (f0) of a site (Nogoshi & Igarashi 1970, Nakamura 1989). When the shear-wave velocity (Vs) contrast between soft sediments and the underlying bedrock is sufficiently large, HVSR analysis of ambient vibrations can reveal this Vs impedance contrast. In regions of unknown subsurface, HVSR is hence a useful method to estimate the depth of the seismic bedrock. Converting f0 to depth (h) is, however, not a straightforward application. In areas with a uniform cover (1D, homogeneous horizontal layers) and a consistent bedrock depth, the mean Vs of the cover can be used to deduce the bedrock depth (h) according to generic formula: h = Vs / (4. f0). However, if the cover and the subsurface geology are heterogeneous, the mean Vs of the cover varies laterally, and the latter equation does not allow to calculate bedrock depth consistently in a region. Another approach to map bedrock depth, is to use the powerlaw relation between h and f0. Van Noten et al. (2022) defined a new powerlaw relation for the Brussels region by first determining f0 from ambient vibration measurements above 78 boreholes in Brussels from which bedrock depth was known. Second, due to the non-linear increase of Vs with increasing bedrock depth, an empirical powerlaw relation was defined according to the following equation:

$$h = 88.631 \, . \, f_0^{-1.683}$$

with a and b defining the position and slope of the regression, respectively. The uncertainty on the prediction of the bedrock depth is 10% according to this method. This relation was widely applied in GeoCamb. Whenever a new borehole was available in the GeoCamb consortium, or through the Win-Win approach, the fo was determined after performing ambient noise measurements above and near the borehole and performing the HVSR analysis. To visualize the results, the HVSR curve was converted into a **Virtual Borehole**, which turned out to be a very effective tool to communicate the geophysical results towards the GeoCamb consortium partners and the general public (Figure 3). More information can be found on the Van Noten et al. (2024) poster presented during the final conference of the GeoCamb project.



☒ Min. 1h record of ambient noise
☒ Record divided in 60s windows
☒ Fourier spectrum analysis
☒ Dividing the Horizontal over Vertical spectra

-> Corresponding peak
= **Resonance frequency**

Sensitive to impedance contrasts and able to detect the thickness of soft sediments over bedrock

Powerlaw relation between resonance frequency and bedrock depth from HVSR above 78 boreholes in Brussels

BRUSSELS, BELGIUM

Application of the powerlaw relation on an HVSR curve to create a **VIRTUAL BOREHOLE**

Figure 3 : Top: Methodology of H/V spectral ratio (HVSR) analysis of ambient noise to determine resonance frequency (f0). The f0 is determined from ambient noise measurements from seismometer or geophone records. Bottom: Powerlaw creation between f0 and bedrock depth/sediment thickness (h) from boreholes in Brussels. The HVSR curve is converted to a VIRTUAL BOREHOLE to communicate results with the general public (after Van Noten et al. 2022).

4.1.2 Working with a new seismic sensor: SmartSolo IGU16HR-3C

The ROB has been installing mobile seismic sensors for active and passive (mainly HVSR analysis) seismic research for decades. These sensors were however not capable of storing long dataseries due to storing and battery limits. The development and availability of industrial seismic nodes for scientific research (end of the year 2010s) changed these limitations. The ROB possesses 34 SmartSolo® IGUHR) 3C sensors. Originally developed for industrial purposes, these instrument strengths feature small size and weight, easy and modular handling, and high robustness with all parts of the seismic instrument in a single casing. These sensors consist of three component geophones with 5 Hz natural frequencies, digitizer that samples between 250 Hz and 4 kHz, internal storage (32 GB), GPS for time synchronization and rough location and a battery that lasts up to one month. With these specifications, the sensors run completely independently.

After the first test and field installations, the obtained results have been beyond expectations in terms of user experience, and sensitivity and accuracy in terms of the recorded seismic waveforms. This was shown in various lab- and field-based tests. The first test aimed for the estimation of the instrument response of the sensors, in order to check if the manufacturer given values are valid. A correct instrument response is essential for the restitution of the recorded waveform signals into true ground motion (e.g., for magnitude estimation). The instrument response has been inverted through the comparison of the recording of coherent seismic signals on two seismic sensors. By installing all 24 sensors in a small grid with 1m x 1m overall size and chopping the data to the recordings of a teleseismic event, we assured high coherence of the recorded waveforms. The manufacturer given values for the instrument response could be confirmed with a misfit smaller than 2%.

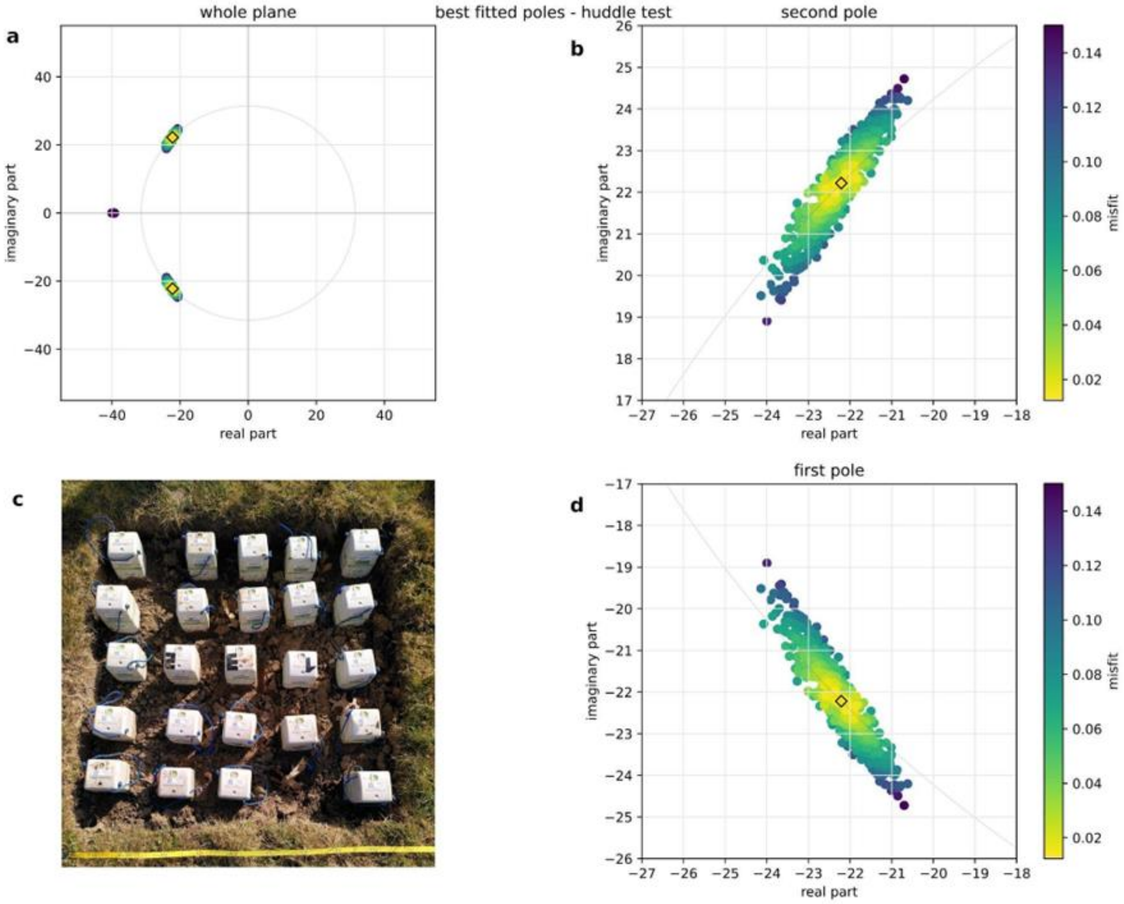


Figure 4: a.) Results of the inversion of the instrument's transfer function represented as Poles plotted in the complex-plane. b+d.) Close-up plot of the two Poles solutions color coded by misfit, with the black diamond showing the manufacturer given value. c.) The full installation of the 24 SmartSolo® in the huddle test, also used for the self-noise estimation.

4.1.3 Evaluation of using non-soil coupled tripod sensors in urban areas

The modular design of the SmartSolo sensors allows the combination of the 3-component sensor with either the default extended battery and a not removable central spike or with the reduced battery pack that is delivered with single component instruments at which the base can be exchanged and replaced by a spike or a tripod. This modularity was very handy during the measurements for the GeoCamb project. Brussels holds a very high degree of urbanization, population density and ground sealing, which prevents the use of a 15 cm long spike for sensor coupling. However, this interoperability of sensor bases also might influence the data quality.

To evaluate if this change of equipment would not alter the recorded noise field, we performed sensor comparison tests in the lab and in the field (at Wiels Cultural Centre in Forest/Vorst).

Figure 5 : Left: Lab-based instrument test of two nodes each based on a tripod or with a spike in a sand-filled bucket next to a classical LE3D/5s (blue pot) seismometer and the well calibrated Guralp sensor of the UCCS permanent station (gray cylinder). Right: Comparison of Lennartz LE3D/5s with city shark digitizer and tripod-based node sensor close the Wiels Cultural Centre in Forest (Brussels).

In the lab-based test (Figure 5- left), we compared the ambient noise recordings of the two types of base set-ups of the node sensors with a Lennartz LE3D/5s sensor (blue sensor) that was used for decades in temporary HVSR measurements and a well-calibrated seismometer of the UCCS permanent station (grey sensor). The investigation of the obtained waveforms in the time and frequency domains lead to highly consistent results for all sensors in the frequency ranges of 0.1 until 15 Hz, which is wider than we expect as fundamental frequency values in the Brussels region (see Figure 4). The quantification of the waveform similarity was reached by computing the coherence amplitudes and spectral divisions of all sensor combinations. As a result, the new nodal sensors give at least comparably good results as the classical Lennartz instrument.

Under real-world conditions we compared the classical Lennartz sensor and the two different bases of the nodal sensor through the comparison of the curves of the Horizontal-to-Vertical-Spectral-Ratio (HVSR) at different locations in Brussels. Under ideal measurement conditions of the UCC permanent station, the HVSR curves are congruent over a very large frequency range, even way below (0.2 Hz), the node’s natural frequency (5 Hz). In the urban context measuring at a busy street in Forest/Vorst, the HVSR curves are becoming unstable and decorrelated at frequency below the site's fundamental frequency (f0). However, the f0 value estimated from the co-located sensors differs less than the range of uncertainty given for the f0 value estimation. The major differences of the sensors are related to their size, weight and installation procedure. The lightweight nodes (see (Figure 5- right) outperform classical seismometer and digitizers in size and weight, enabling a single operator to install 4 node sensors in the time of one Lennartz-Cityshark instrument set. Further, operators become independent from vehicles in order to reach measurement sites in the high-density urban area; many sites in the GeoCamb project have been reached by bicycle. One drawback of the fixed tripod on the nodes is the lack of levelling of the instrument, which rather relies on even surfaces and the poorer coupling than with the spikes.

The results of this study have been submitted as a preprint on the EarthArxiv server in September 2022 (Zeckra et al. 2022).

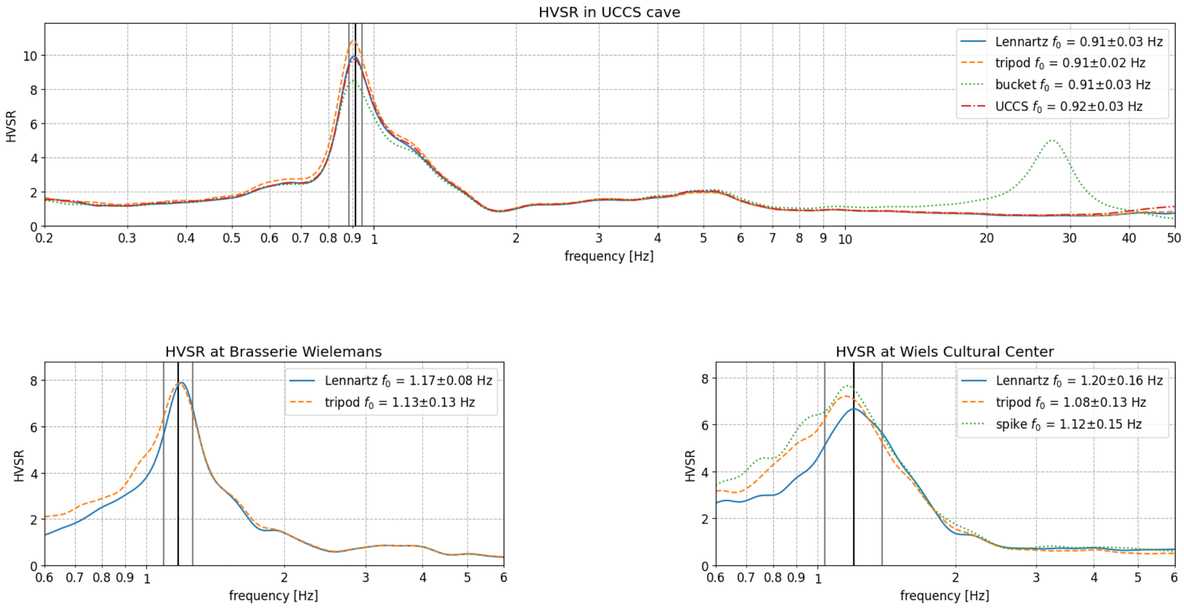


Figure 6 : Instrument comparison through H/V analysis at three locations in Brussels. Waveforms have been restituted before the processing. HVSR graph from recordings a) at the locationof UCC surface sensor (50.7973N, 4.3605E) from the sensor comparison lab test (fig. 3), withthe blue solid line for LE3D-5s with Cityshark, orange dashed line for SmartSolo node on tripodbase, green dotted line for node with spike in a sandfilled bucket and red dot-dashed line for Guralp permanent sensor. b) Location of the former Wielemans Brewery (50.8261N, 4.32646E) with LE3D-5s and Smartsolo sensors ~10 cm apart. c) Location at the Wiels Cultural Center (50.82453N, 4.3259E) with LE3D-5s, node on tripod and node with spike digged into a grassfield. Intersensor distance 5 - 10 m.

4.2. GeoCamb case-study of social building renovation at Molenbeek

4.2.1. General project, potential building site

A feasibility study for the renovation of the Ghandi apartment buildings, located on Avenue Mahatma Gandhi in Molenbeek, has been conducted by the Logement Molenbeekois. The 5 modernistic buildings date from 1970 until 1981 and are in need of a thorough refurbishment, which offers opportunities towards a deep renovation of the heating and ventilation systems as well.

Figure 7. Ghandi apartment blocks.

Moreover, the site is located promisingly between two known and running aquifer thermal energy storages (T&T and the Broeckhoven school) and there is enough open space surrounding the buildings for (exploratory) drillings. We decided to focus on the oldest building Ghandi nr. 2, since it is also the first to be renovated. It is the most on the left in Figure 7, with in total 14 floors and 56 apartments. Off course if it is to be decided to use geothermal energy as a heating and cooling source for this building, it is interesting to scale up the solution towards the other 4 apartment buildings and work towards a micro heating network. If we keep this network at low temperatures, close to the geothermal source temperature, it can be built at lower cost and be used for heating in winter, and cooling in summer (heating network of the 5'th generation). There are other public buildings in the neighbourhood (sport facilities, a large secondary school, etc.) that could benefit from this investment and be added to the geothermal driven network.

One level of the building nr.2 has been simulated with the BESP Design Builder™, to assess the heating and cooling profile before and after possible renovation scenarios.

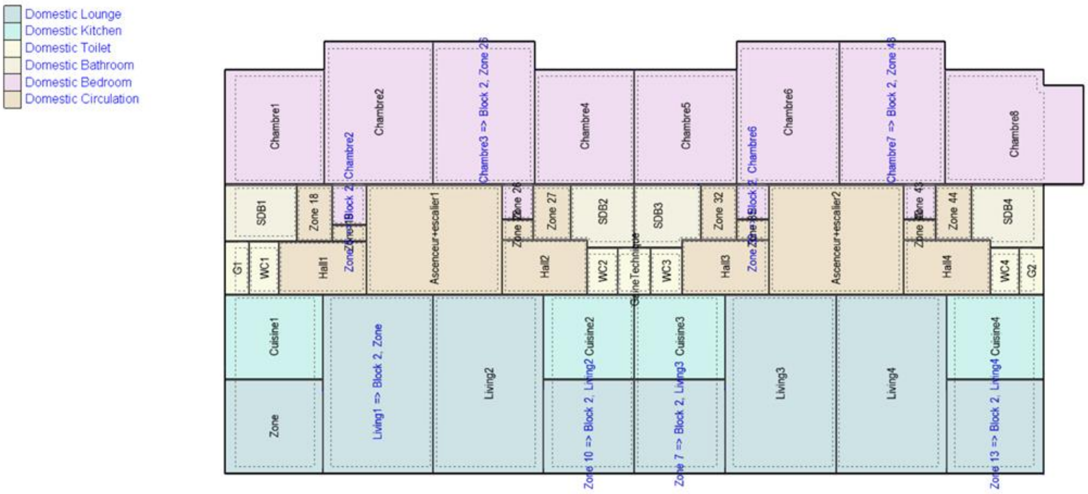


Figure 8 Layout of one apartment building floor used to run the dynamic energy simulations

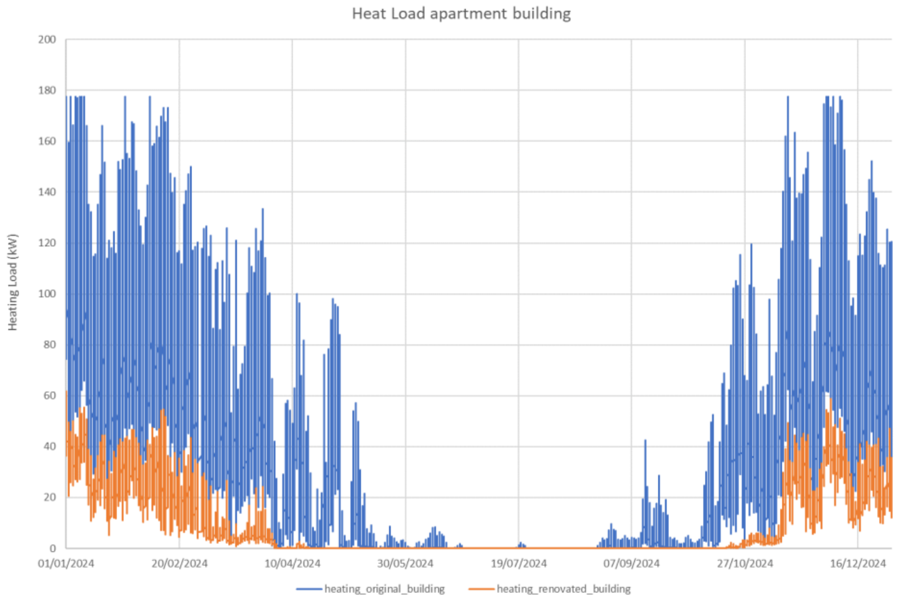


Figure 9: Simulated heat load profiles of Ghandi nr. 2 before and after a thorough renovation

The simulation results show the large impact of the new building envelope (Figure 9), the heating power drops from 180 kW towards 60 kW, while the energy demands is reduced by a factor 4 (from 285 MWh to 70 MWh). This reduction in heat demand could offer the possibility to re-use the current radiators at an ideal temperature of 40/30°C! Only in the bath rooms there would be a need for an electrical back-up heater (or a larger radiator) to maintain the (high) comfort temperature there. However, since the new envelope is planned to be moved towards the outside of the balconies (to increase the size of the living area of the apartments) and the current radiators are deemed to be too heavy and too old, this scenario is not preferred by the building owner.

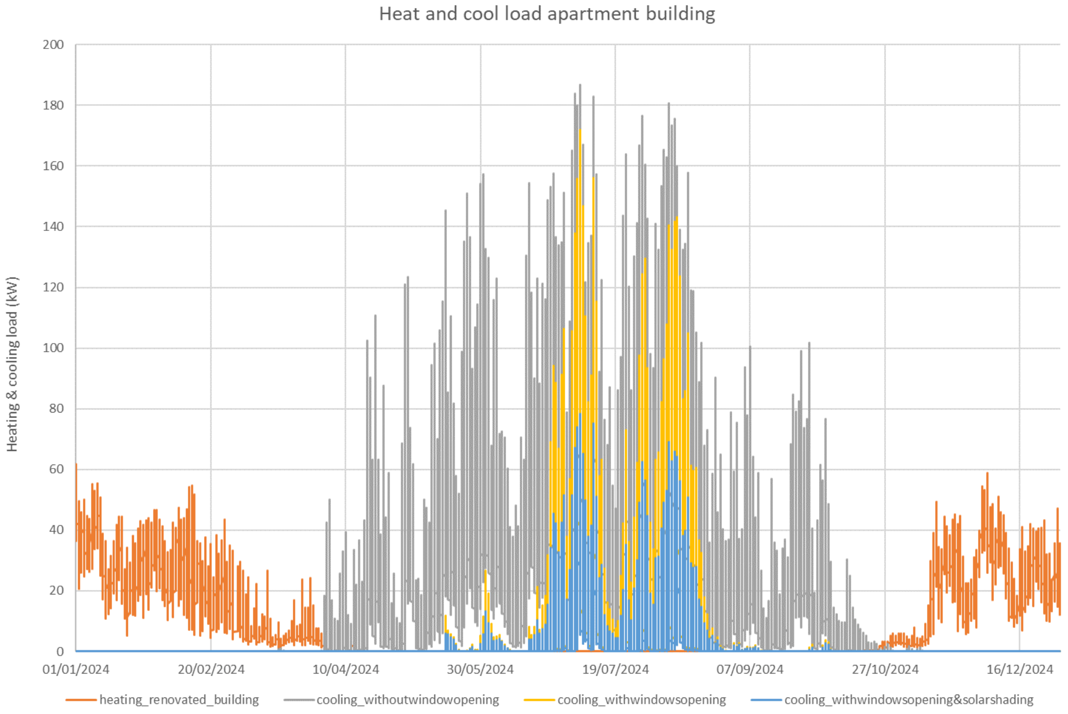


Figure 10: Simulated heating and 3 possible cooling profiles for Ghandi nr. 2 after the thorough renovation

Moreover, if we look at the projected cooling demand, it is clear that we will need emitters that are also capable of delivering enough cooling energy. In fact, cooling becomes the predominant dimensioning factor. If we wouldn't apply any passive cooling measures, the necessary cooling power would be close to 180 kW and thus three times higher than the heating power. Also the energy balance would be totally skewed towards cooling, leading to imbalance problems in the geothermal source. If we add a thorough night ventilation scheme (only opening the windows when the outside temperature drops below the indoor temperature), the energy balance between the projected heating and cooling can be restored, but the necessary cooling power remains high during heat waves in summer.

This high cooling power need would mean that the geothermal source needs to be dimensioned on the cooling demand and power. An open source would be preferably since we can deliver as much free cooling energy as we have cooled down the source during the heating time at winter. This is not the case for a closed geothermal source, where the potential for free cooling is limited to about a third of the heating demand. If we would need to build a closed geothermal system, we should advise to look for other buildings in the neighbourhood with larger heat demands, so we can create the right heating/cooling ratio.

Moreover, also for the emitters a large cooling power is not easy to deliver, certainly not at higher cooling temperatures (eg. 18°C) that would be ideal for a free geothermal cooling source. We would need to look at emitters used in typical office environments, such as ceiling cooling or ventilo-convectors. Due to stratification, floor heating systems can deliver less cooling power than ceiling cooling. For both systems it is important to combine the surface cooling with a precooling and dehumidification of the ventilation air, so that there would be no condensation risk in the apartments. This adds up to the investment costs. An alternative would be to install ventilo-convectors and use a reversible heat pump to cool down the source temperature towards 7°C, so that enough cooling power can be emitted in the rooms.

For the reasons mentioned above, it is advised to the Logement Molenbeekois to add solar shading to the renovation. This will reduce the cooling power and cooling energy demand even further, so that the cooling power is at the same level as the heating power, and the cooling demand is only about one third of the heating demand. This opens up possibilities towards closed loop geothermal systems and a broader choice of heat emitters inside the building (more information can be found in the building energy report for Logement Molenbeekois).

To conclude and generalize this building energy feasibility study:

- A refurbishment of the building envelope creates opportunities for heating at lower temperatures and thus ideal conditions for heat pumps and geothermal sources.
- We should be aware for increased cooling needs after the renovation. The inclusion of passive cooling measures such as solar shading and ventilative cooling is necessary to keep a balance between heating and cooling, important for the geothermal source but also towards the selection and dimensioning of the systems in the building.
- If the cooling demand and cooling power can be controlled, the combination of free geothermal cooling and surface heating/cooling systems can be used, preferably also with a conditioning of the ventilation air. Otherwise active cooling systems (reversible heat pump)

and ventilo-convectors working at low temperatures (air cooling and condensation outlets) are necessary.

Since the potential for geothermal source to be coupled to the building(s), the following tests were carried out:

- Geophysical ambient noise measurements in June 2021
- Exploratory drilling to a depth of 151.5 meters in October 2022 (RBINS-SGB).
- A geophysical logging (UGent) on October 20, 2022.
- Pumping tests in March 2023.
- An enhanced Thermal Response Test (e-TRT) in April 2023

The collaboration between Logement Molenbeekois and the GeoCamb partners, and therefore the "geothermal prefeasibility study" (the drilling results, geophysical loggings, pumping tests, thermal response test , and the energy profile of Building 2), aimed to evaluate the geothermal potential (geology, water inflow, potential for an open or closed system, etc.) but does not in any way result in the creation of a geothermal system.

The geothermal prefeasibility study conducted by GeoCamb is by no means sufficient to install an open geothermal system in the buildings on the "Gandhi" site of Logement Molenbeekois in Molenbeek-Saint-Jean. However, it provides crucial elements to consider if geothermal energy is to be utilized as part of the site renovation.

4.2.2. Geophysical reconnaissance

Before drilling was planned, a geophysical reconnaissance next to buildings 1, 2 and 3 took place on 1st of July 2021. The ROB placed seven SmartSolo IGU-16HR 3C geophones and two Lennartz 3D-5s sensors for 1.5 hour to determine resonance frequency around the buildings and converting the results to virtual boreholes. The geological map below shows the results of this short analysis. The resonance frequency ranges between 0.90 and 0.95 Hz. There are slight differences between the measurements and bedrock depth ranges between 97 m and 104 m depth around the building of interest (nr. 2 on the map Figure 11). The measurement closest to the GeoCamb geothermal test well (see below) predicts a bedrock depth of 99 m. On average, bedrock depth is 100.5 m. This value matches exactly the bedrock depth of 100.5 m in the current model of the virtual borehole BruGeoTool, which again shows the power of the HVSR technique and usefulness of performing geophysical measurements before drilling.

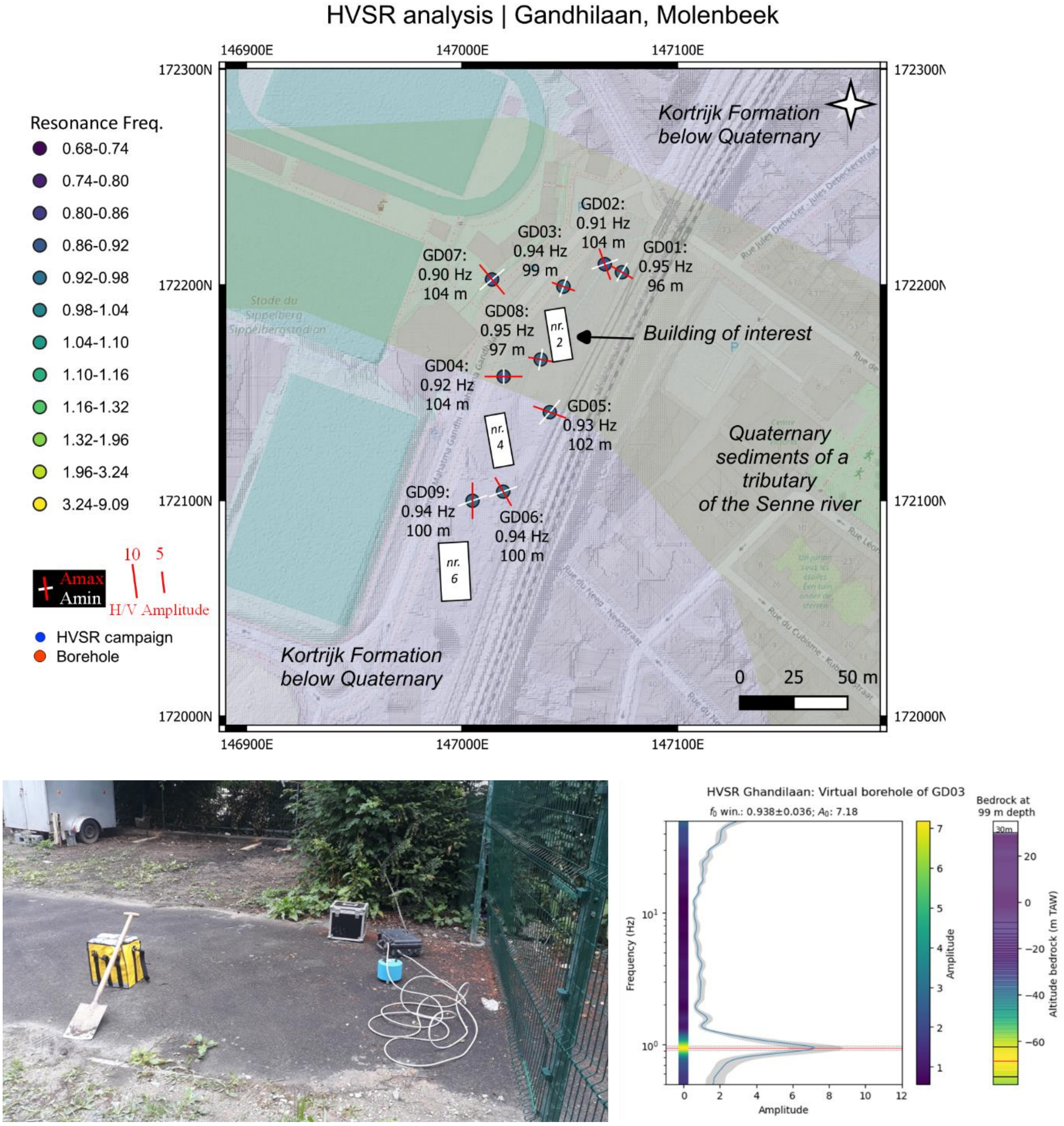


Figure 11 Top: HVSR results and corresponding bedrock depth values illustrated on a geological map around the building of interest, Ghandilaan nr. 2, Molenbeek. Bottom: Photo and Virtual borehole of the geophysical measurement closest to the GeoCamb geothermal test well.

4.2.3. Drilling

The geological and geothermal reconnaissance drilling was carried out between October 3, 2022, and October 19, 2022, by RBINS on behalf of *Logement Molenbeekois*. This drilling, located 2 Mahatma Gandhi Avenue, is part of the feasibility study for the renovation and redevelopment of the "Gandhi" site in Molenbeek-Saint-Jean (see Figure 12).

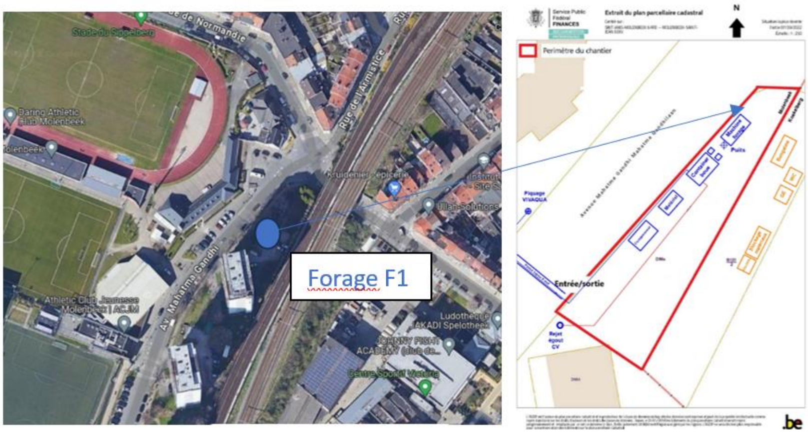


Figure 12: Location of the Moleenbeek-Gandhi drilling site

Through this exploratory drilling, the composition of the Mesozoic-Cenozoic cover and the Paleozoic basement (of the Brabant Massif, of Cambrian age) has been determined. The report on the Gandhi exploratory drilling is available in Annex 1.

Following analysis (see the stratigraphic log of the drilling **Error! Reference source not found.**), the geological interpretation of the collected samples led to the following conclusions:

- The unconsolidated layers of the Ceno-Mesozoic were encountered over a thickness of approximately 93 meters (Courtrai and Hannut Formations).
- The Gulpen Formation (Cretaceous) represents a thickness of about 7 to 8 meters.
- The Paleozoic basement, represented here by the Tubize Formation (Cambrian), was reached at a depth of 101.5 meters, which almost exactly matches with geophysical reconnaissance values. More than 50 meters of coring were conducted within this geological horizon (**Error! Reference source not found.Error! Reference source not found.**).

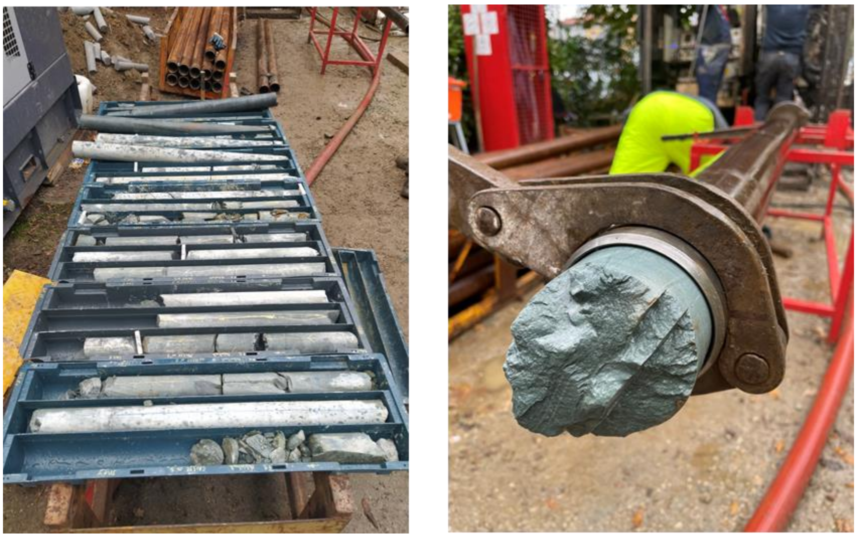


Figure 13 Pictures of the Molenbeek-Gandhi drilling cores (50m were cored), the left picture reveals the steep dip of the cores.

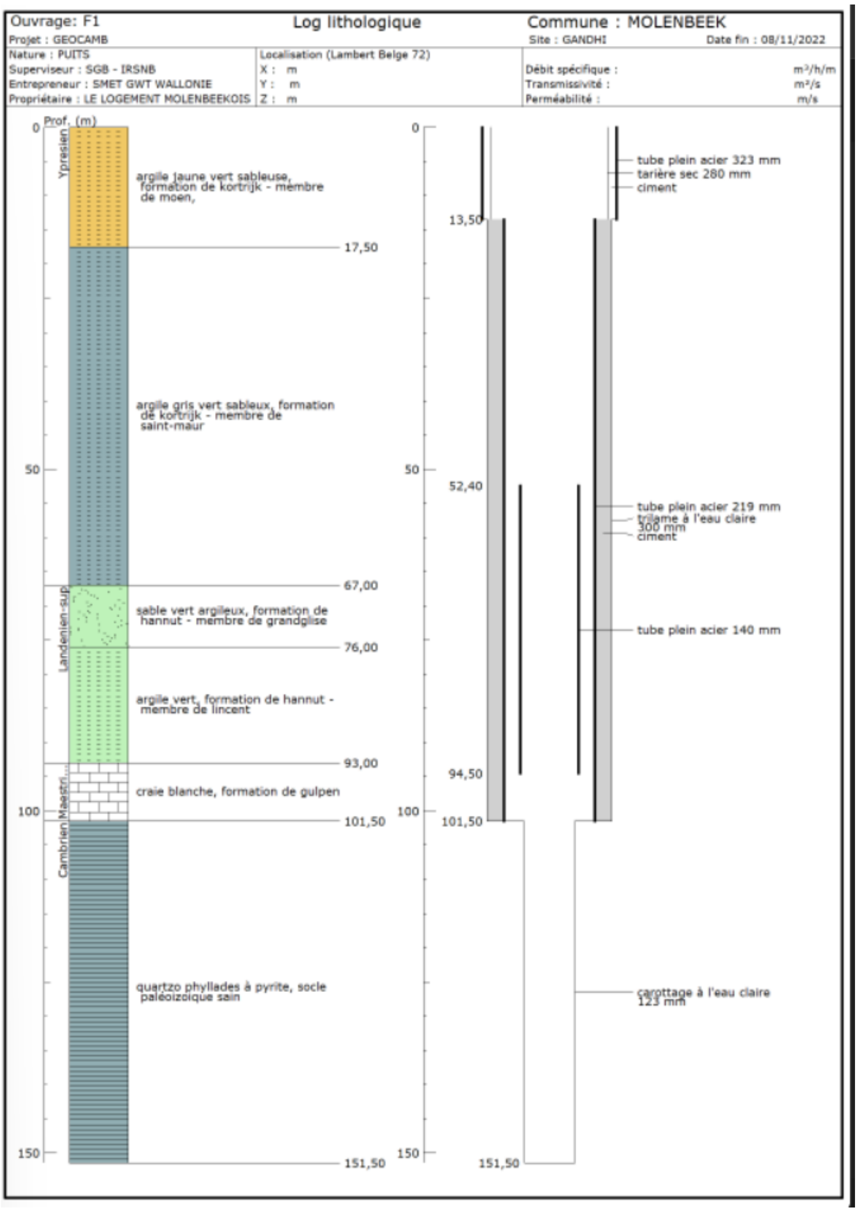


Figure 14 Lithostratigraphic log simplified and borehole equipment of the Molenbeek-Gandhi drilling.

The detailed analysis (sedimentology and fractures analysis) of the cores was carried out at RBINS-GSB. The dip angle in a core refers to the angle at which geological features (such as bedding planes, fractures, faults, or foliations) intersect the core axis. It provides crucial information about the orientation of these features in the subsurface, which is vital for understanding the geology and structure of the area being drilled. The dip angle of Molenbeek-Gandhi cores evolves from 50° to 90°, the number of fractures is very variable along the 50 meters of cores (see example Figure 15).Some long cores sections are devoid of fractures.

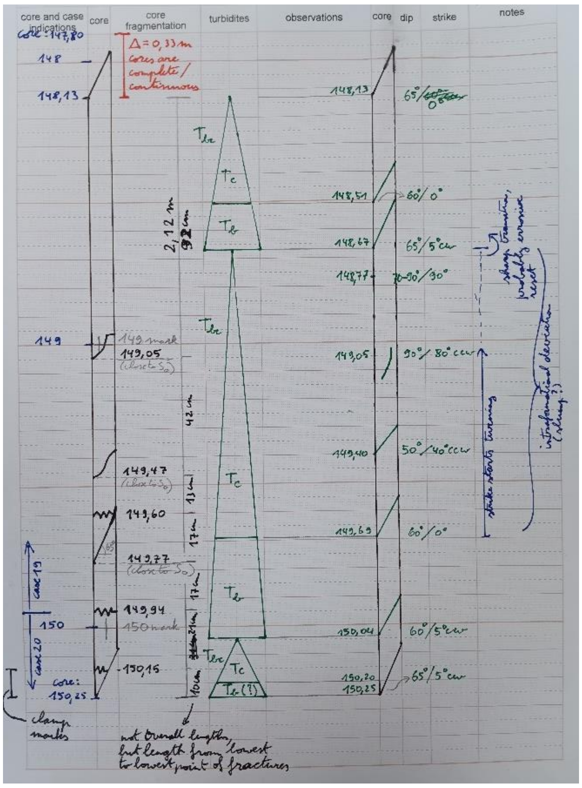


Figure 15: Example of core analysis of Molenbeek drilling with core fragmentation, turbidites types, dip and strike angles.

Dip angles ranging from 50° to 90° suggest that the geological features (e.g., bedding planes, faults, or foliations) in the Brabant Massif are almost uniformly steeply inclined, but not overturned. This steep inclination is commonly associated with regions that have undergone significant tectonic deformation, such as folding and faulting, typically linked to orogenic events (Caledonian, Variscan and Alpine orogenies). The steep dips indicate intense tectonic stresses, possibly linked to compression or thrusting during past orogenic events. These dips may correspond to: Tight folds with steep limbs/ High-angle reverse faults or thrusts/Tilted fault blocks or reactivated basement structures. Steep dips often coincide with increased fracturing, which can enhance permeability in the subsurface. This is especially relevant for geothermal energy exploration, as fractures can act as pathways for fluid circulation. The fractures may intersect heat-producing zones, enhancing the geothermal gradient and fluid flow.

The cores belong to the Tubize formation, which is a very distal facies in this drilling. Locally some reddish coloration is observed at the shallowest depths. The colour is slightly less ‘chlorite-like’ than what is typically expected. The first meters are paleo-weathered, but not extensively. Enough to give them that smooth and kaoline-touch. Around the Quartz-vein at about 120 m there is nice hydrothermal alteration (not paleoweathering) visible as coloration of the silt-layers. Deeper, the chaotic appearance is not due to tectonic deformation, but cross-lamination and synsedimentary deformation. This also corresponds to a facies change (more proximal).

4.2.4. Geophysical Logging

Borehole logging is a geophysical method used to measure, with various probes, the characteristics of rocks encountered during drilling. Generally, borehole logging refers to the continuous recording of a geological formation’s properties as a function of depth. The objective is to acquire physical (mechanical, thermal, hydraulic, electrical) or chemical parameters directly or indirectly related to the rock's characteristics at depth.

In the study conducted in borehole F1 Gandhi-Molenbeek, five measurements were recorded:

- **Caliper (borehole diameter)**
- **Natural Gamma Radiation (NGR)**
- **Density/Porosity (Neutron Log, NL)**
- **Electrical Resistivity (RES)**
- **Spontaneous Polarization (SP)**

Details of Each Measurement

Caliper (Borehole Diameter) : The caliper uses arms that open during upward movement to measure the borehole's actual diameter across several diagonals. The caliper data provide insights into:

a. The stability of the borehole walls and the mobility of certain formations.
b. Feasibility of casing installation or the need for reaming.
c. Cement volume estimation.
d. Setting depths of previous casings.
e. Relative estimation of formation pressure compared to drilling fluid density (uniform caving).
f. Presence of compressive tectonic stress (differential caving).
g. Identification of faults.

Natural Gamma Radiation (NGR) : Natural Gamma Radiation corresponds to the natural emission of gamma radioactivity from rocks. Rocks rich in radioactive elements (like clays) show higher gamma ray (GR) values. Measured in counts per second (cps), this value is proportional to the energy of the incident gamma radiation. In sedimentary rocks, gamma activity typically ranges from 0 to 200 API.

Electrical Resistivity (RES): Resistivity logging refines the lithological understanding of formations. Resistivity is the electrical resistance of a rock cube with unit edge length, measured in ohm-meters. Influencing factors include:

h. Rock composition (solid grains, crystals, cements) and fluid content (water, hydrocarbons).
i. Porosity and pore saturation with fluids.
j. Rock texture (grain size, arrangement, cement volume).
k. Distribution of conductive minerals.
l. Structural characteristics (homogeneous, fractured, laminated).
m. Temperature (higher temperatures increase conductivity).

Rocks with connected pores allow current to pass through water in the pores. A porous formation containing saltwater will have lower resistivity than one with hydrocarbons or irreducible water.

Density/Porosity (Neutron Log, NL) : Neutron logging measures density through neutron interactions. Tools emit neutrons, which collide with hydrogen atoms, losing energy and slowing down until reaching a thermal state. The rate of thermalization correlates with the hydrogen index (HI), converted into neutron porosity.

Spontaneous Polarization (SP) : Spontaneous Polarization reflects the natural polarization of borehole walls due to interactions between formation fluids' ions and drilling mud filtrate ions. SP is measured as the potential difference between a stationary surface electrode and a mobile downhole electrode.

Results

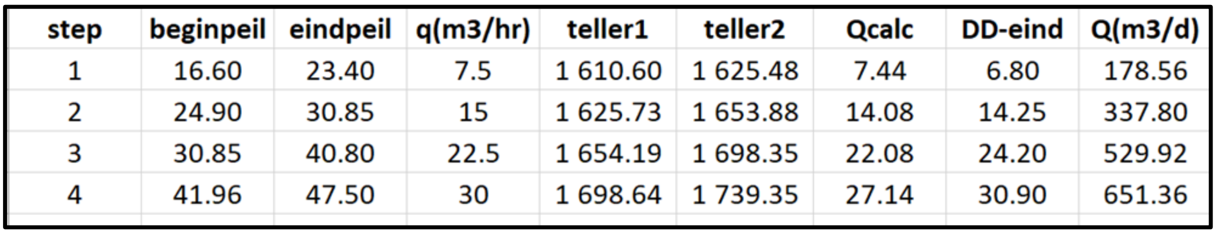
An **iron casing** was placed through the unconsolidated layers to the basement's top at 101.5 m and cemented.

- **At 101.5 m:** A caliper spike indicates a thin sediment layer removed just below the casing.
- **Basement (101.5–120 m):** The top of the basement is altered, evidenced by:
    - Frequent caliper excursions.
    - High natural gamma radiation (likely from clay alteration).
    - Low resistivity.
    - High SP values, indicating fresh groundwater.
- **Below 120 m:** Rocks are more compact, but a **fractured zone at ~128–132 m** is identified from caliper, resistivity, and SP data.
- **Between 143–147 m:** Three distinct gamma ray spikes and corresponding resistivity troughs, alongside high SP values, suggest fractures not detected by the caliper, possibly because they are too narrow.

These results provided critical insights into borehole stability, lithological characteristics, and potential hydrogeological features within the F1 Gandhi-Molenbeek site. The results are presented in Annex 1.

4.2.5. Pumping tests

The step-drawdown test at the Molenbeek well was performed on 22 March 2023 with the following characteristics:



step	beginpeil	eindpeil	q(m3/hr)	teller1	teller2	Qcalc	DD-eind	Q(m3/d)
1	16.60	23.40	7.5	1 610.60	1 625.48	7.44	6.80	178.56
2	24.90	30.85	15	1 625.73	1 653.88	14.08	14.25	337.80
3	30.85	40.80	22.5	1 654.19	1 698.35	22.08	24.20	529.92
4	41.96	47.50	30	1 698.64	1 739.35	27.14	30.90	651.36

Figure 16 Step-drawdown test characteristics of Molenbeek-Gandhi case-study.

The water level was monitored (**Error! Reference source not found.**) by a pressure transducer ("Diver") that was installed on 21 March 2023, when some preliminary test pumping was performed.

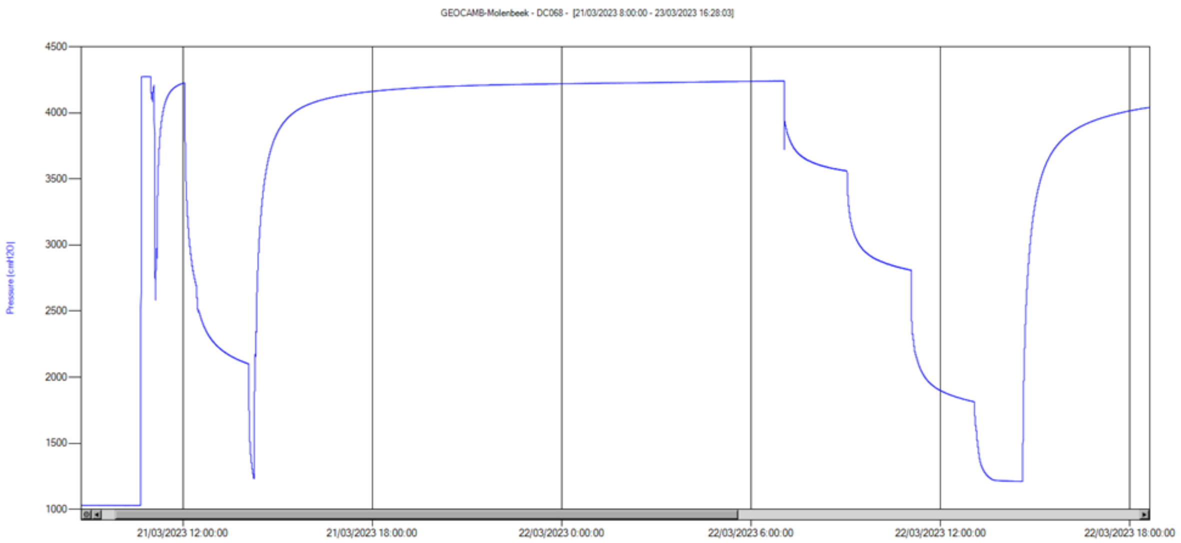
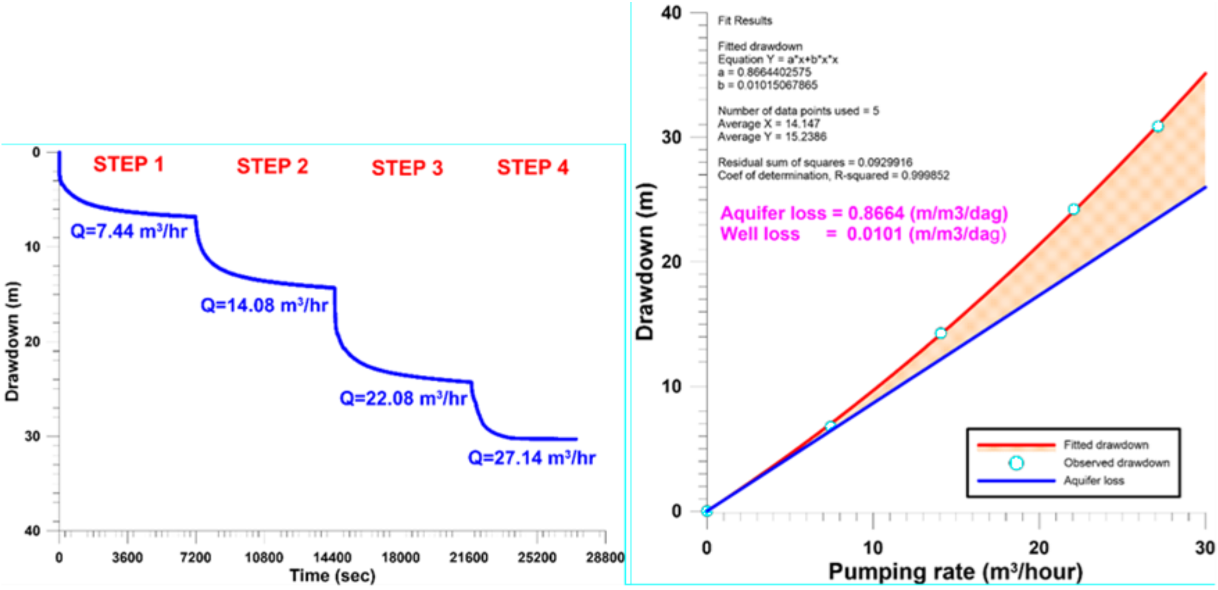


Figure 17: Water level monitoring in the Molenbeek-Gandhi borehole

The four steps of the step-drawdown test are represented in the **Error! Reference source not found.**. The test was interpreted twofold: at first with the (conventional) method of Eden-Hazel, and next with the analytical solution of Barker (1988) using the concept of fractional flow dimension (see section 3.2).

The method of Eden-Hazel allows to distinguish well loss from aquifer loss. The aquifer loss in the Molenbeek well was found to be 0.8664 m/(m³/day), while the well loss was quantified as 0.0101 m/(m³/day). As can be deduced from Figure 10, at a discharge rate of 20 m³/day, some 4 m drawdown is due to the well, while some 17.5 m drawdown is due to the aquifer. Well loss increases with increasing discharge rate.



```
Fit Results

Fitted drawdown
Equation Y = a*x+b*x*x
a = 0.8664402575
b = 0.01015067865

Number of data points used = 5
Average X = 14.147
Average Y = 15.2386

Residual sum of squares = 0.0929916
Coef of determination, R-squared = 0.999852
```

Figure 18: The four steps of the step-drawdown, well loss and aquifer loss calculations

The interpretation of the step-drawdown test with the method of Eden-Hazel results (**Error! Reference source not found.**) in a transmissivity value of 15.51 m²/day, for the well that has been drilled for 50 m into the Basement rocks (from 101.5 m to 151.5 m). Average hydraulic conductivity is thus quite small (0.31 m/day).

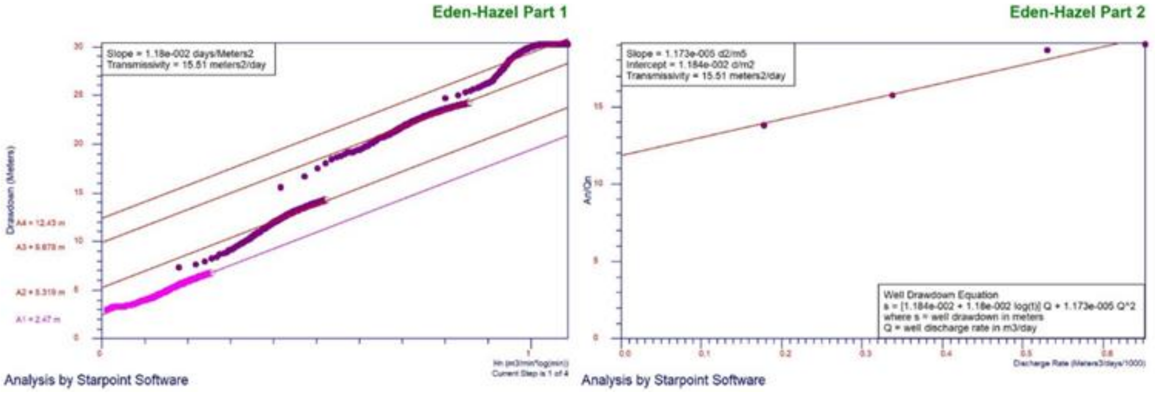
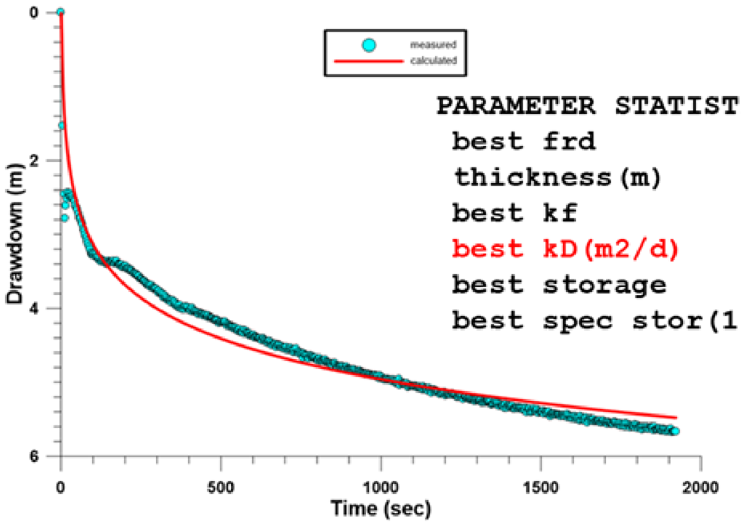


Figure 19: Interpretation of the step-drawdown test with the method of Eden-Hazel

Application of the analytical solution of Barker (1988), for the first phase of the step-drawdown test, resulted in value of 2 for the fractional flow dimension, indicating radial flow (**Error! Reference source not found.**). Deduced transmissivity is 16.87 m²/day (average hydraulic conductivity is 0.34 m/day), while storage is 0.00659 (and average specific storage is 0.00013 m^{-1}).



```
PARAMETER STATISTICS:
 best frd               =    2.00099993
 thickness(m)           =    50.0000000
 best kf                =   0.337420732
 best kD(m2/d)          =    16.8710365
 best storage           =    6.59569539E-03
 best spec stor(1/m)    =    1.31913912E-04
```

Figure 20: Analytical solution of Barker (1988) of the Molenbeek-Gandhi step drawdown test.

4.2.6. Enhanced Thermal Response Test

Knowledge of the local geology is essential for the design of a geothermal system. For the design of closed loop geothermal systems, thermal ground parameters are crucial. These parameters are site-specific, and in situ measurements are therefore necessary to accurately determine them. An Enhanced Thermal Response Test (ETRT) was conducted on the exploratory borehole. This test uses a hybrid cable (combining copper heating cables and a fiber optic cable). The fiber optic cable allows for temperature measurements with high spatial resolution (up to every 0.5m along the cable). During the ETRT, an electrical current is sent through the copper cable(s) of the hybrid cable. Simultaneously, the resulting temperature change along the fiber optics is recorded. By applying the theory of linear or cylindrical heat sources, the subsoil thermal parameters can be determined accurately and with high spatial resolution.

The results of the ETRT conducted in the borehole at the Ghandi site (150 meters deep) are presented in **Error! Reference source not found.**. The undisturbed (or initial) temperature profile is the average of the measurements taken during the 24 hours prior to the start of the heating phase. Thermal conductivity values are calculated from the temperature measurements during the recovery phase.

For the exploratory borehole, an average undisturbed ground temperature of 12.04 °C and an average thermal conductivity of 2.73 W/mK was determined. The thermal conductivities calculated for the upper soft soil layers and for the Cambrian bedrock are 1.89 W/mK and 3.80 W/mK, respectively.

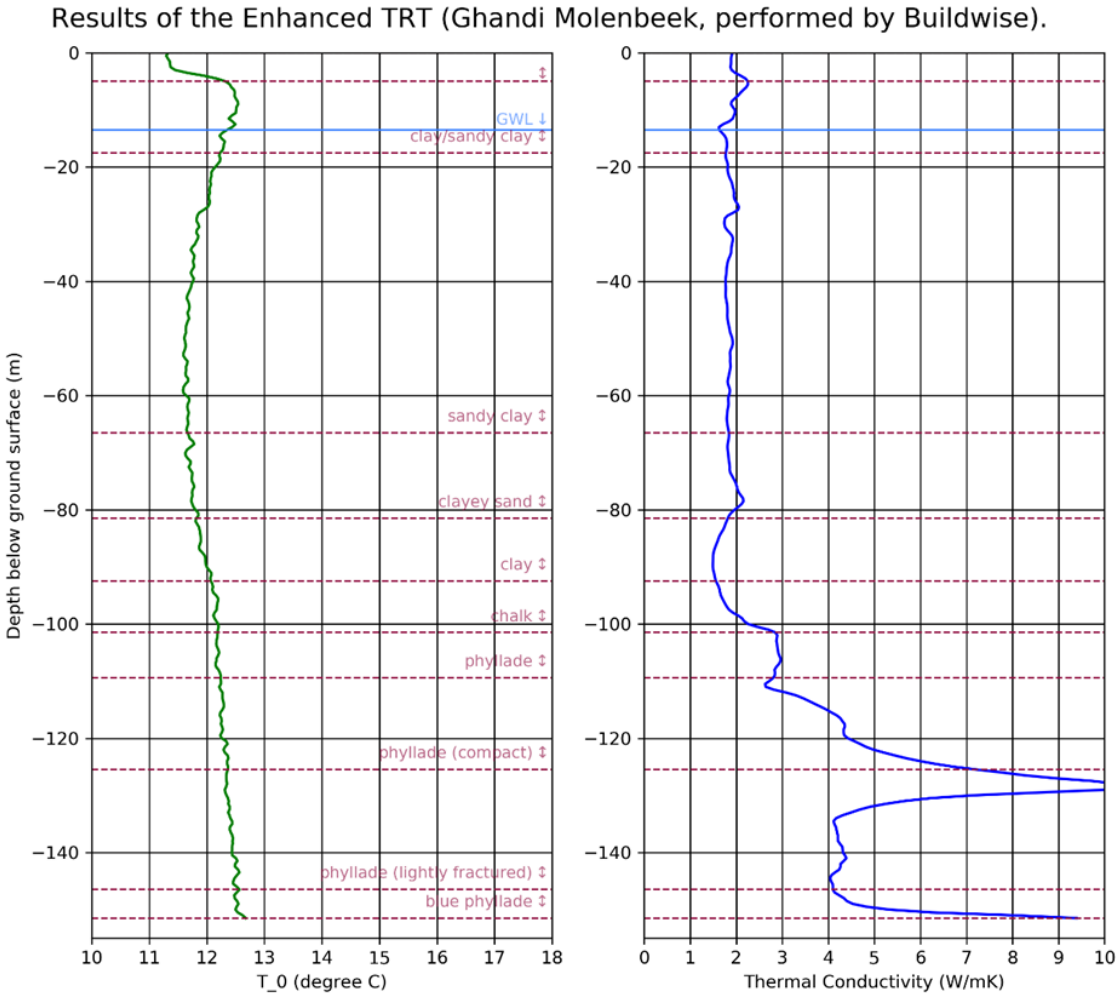


Figure 21 : Results of the ETRT performed in a 150 meter deep exploratory well at Molenbeek (left : undisturbed temperature - right : thermal conductivity)

4.3. Interferences between open geothermal systems: the Tour & Taxis study

Three ATES (Aquifer Thermal Energy Storage) systems located in two different aquifers in the center of Brussels in the Tour & Taxi site are already operated for heating and cooling in three different recent or recently renovated buildings located in an urban reallocation zone of Brussels (Figure 22). The first one was started in March 2014 (Building 1), the second in August 2017 (Building 2), and the third (located in the Cambrian aquifer) in April 2020 (Building 3).

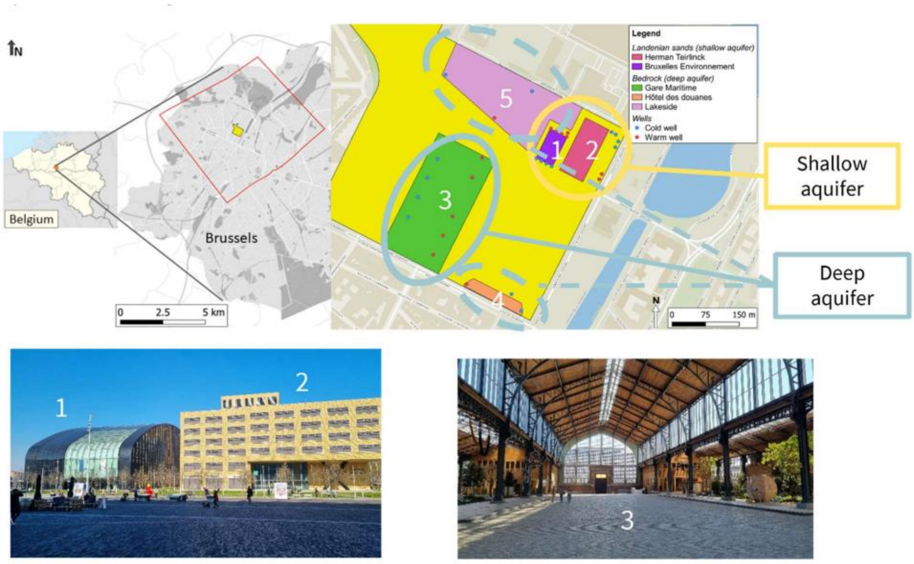


Figure 22: Location of the Tour & Taxi site, and the different buildings. Buildings 1 and 2 are pumping and reinjecting groundwater in the Cenozoic aquifer, buildings 3 to 5 in the Cambrian aquifer. The geothermal systems of buildings 4 and 5 have not yet started to be operational.

Three of these adjacent shallow open-loop systems (ATES) were studied previously by Artesia and ULG. For two of them, operations started in 2014 and 2017 respectively with pumping and reinjection wells in Cenozoic mixed sandy and silty shallow formations. The third one, a larger ATES system (Gare Maritime) was started in 2020 with 5 doublets of wells in the Cambrian fractured phyllites and quartzites to provide heating and cooling power to a large multi-service building. The cumulative effect of the three first geothermal installations was previously investigated using Feflow©. In terms of heat interactions, the model showed how the first ATES system's thermal imbalance affected the upper aquifer (Bulté et al. 2021) and thus also affected the second ATES system. Then, adding the third system in the deep Cambrian aquifer, relatively small interactions were simulated through the aquitard formed by low permeability Cretaceous base deposits and the weathered top of the bedrock (De Paoli et al. 2023).

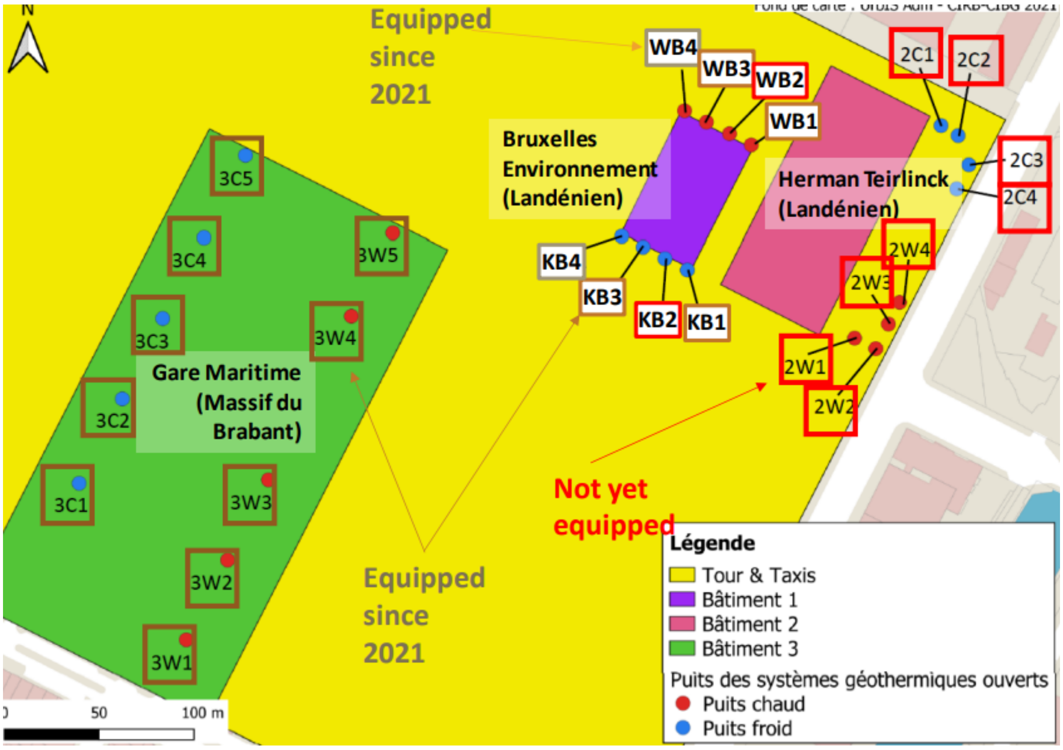


Figure 23 Location of wells monitored in the T&T site: 10 wells of Gare Maritime and 6 wells of Brussels Environment building.

End of 2023, two new ATES systems are planned with wells in the Cambrian (1) one ATES for building 4 (Hotel des Douanes) that is corresponding to a renovated old hotel that will be used probably for housing and offices and (2) a second ATES for building 5 (Lakeside project) that will correspond to a large and more dispersed ensemble of housing, offices and retails activities. At this stage, and on basis of the available data when this study was done, one hot well and two cold wells were foreseen for building 4, and two doublets of hot and cold wells were planned for building 5 .

The research work is thus extended including the two new ATES systems and their impact and interactions are simulated. Also, the acquisition of recent measured data (i.e., potentiometric heads, groundwater temperatures, detailed pumping, injection flow rate, etc.) has allowed to improve the Feflow 3D model. First results are shown illustrating the sensitivity of the ATES interactions to an adequate hydrogeological characterization. The model results are also very useful to guide the optimized future management of the five adjacent ATES systems to prevent losses in efficiency for some (or all) of them. The details of these simulations are available in Annex 2.

From these simulations, using a Feflow 3D heterogeneous groundwater flow and heat transport model, a series of lessons can be deduced.

a) The local advection component (due to the groundwater flow in the aquifers) of the heat transport remains weak in comparison of the conduction in both the Cenozoic and Cambrian aquifers. The hydrogeological conditions are in fact optimum for a consequent heat storage of heat or cold without significant losses. This means also that the geothermal systems should be, as far as possible, thermally balanced in heating and cooling demand to avoid long term changes in the aquifers temperatures. If this is not the case, the future efficiency of the ATES systems will decrease accordingly.

b) At this stage of our hydrogeological understanding of the local conditions, limited heat transfers are simulated between the Cenozoic and the Cambrian aquifers through the clays of the Lower Hannut Formation and the marly Gulpen Formation. This leads to results showing very limited interactions between ATES systems located in the different aquifers, and thus a very limited impact on the efficiency of these systems.

c) New data should be collected especially piezometric heads and temperature in monitoring wells independent from the hot and cold wells of the five ATES systems. Ideally, three monitoring wells screened in the Cenozoic aquifer and three monitoring wells screened in the Cambrian aquifer would provide nice data sets for a future better optimization of the five ATES management, and for a check of the impacts on both aquifers. Another option could be to use DTS temperature sensors in filled boreholes.

d) Data about the actual (real) heating and cooling consumptions of each building should be collected in order to allow more realistic simulations with regards to the reality.

e) The existing Feflow model could easily be further adapted, refined, and used for any new scenario changing the hydrogeological and thermal condition in these two aquifers.

Geophysical exploration around the Tour et Taxis site

On 2 December 2022, an extensive field day was performed with the help of the Ma1 students of the ULB at the Tour et Taxis (T&T) site in Brussels. 21 SmartSolo seismic nodes, one 5s SmartSolo instrument and two Citysharks were installed along the whole length of the Lakenveldsquare park (~1550 m) with a node spacing of ~100 m, starting from the Havenlaan (building of the Flemish Government). Goal was to test the DOV and BruGeo 3D geological model of the top of the Brabant Massif using geophysical measurements and the HVSR technique. The resonance frequency (indicative of the sediment and bedrock interface) was converted to depth using the Van Noten et al. (2022) powerlaw. The results (see Figure 24) confirm the northwards dip of the Brabant Massif. However, the geophysical measurements around Tour et Taxis show that the bedrock is deeper than the BruGeo 3D model currently indicates.

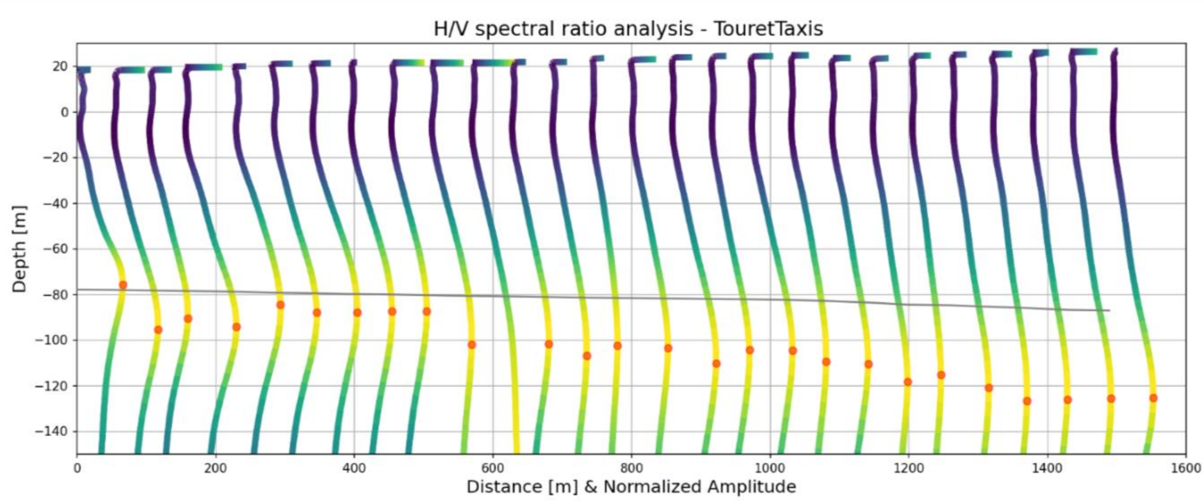


Figure 24 : Top: Map of installation of seismic nodes around the Tour et Taxis site. Bottom: Tour et Taxis bedrock depth cross-profile from Brussels Environnement building towards the NE. Red dots indicate the highest contrast between sediment and bedrock obtained by converting resonance frequency to depth using the Van Noten et. al (2022) powerlaw. The grey solid line indicates the current BruGeo top of the Brabant Massif.

4.4. Demonstration of the performance of geothermal systems

4.4.1. Introduction

The performance of 3 geothermal systems was studied during the project:

- Case 1: office building in the Brussels city centre[1]: closed loop or Borehole Thermal Energy Storage (BTES) system, covering a part of the building's heating and cooling demand.
- Case 2: office building of AGC (Louvain-La-Neuve): closed loop or BTES system, covering the entire heating demand of the building and a part of the cooling demand.
- Case 3: Gare Maritime building (Tour and Taxis): open loop or Aquifer Thermal Energy Storage (ATES) system, covering the heat and cold demand of the building units inside Gare Maritime.

To properly evaluate and demonstrate the performance and efficiency of a geothermal system, several key aspects must be addressed. The process begins with collecting general information about the geothermal field, ground lithology, and the control system in place. This information provides the necessary context for further analysis. Then, monitoring includes the logging of fluid or groundwater temperatures, the energy flows both underground and within the building. Data of electricity consumption and indoor building temperatures have a large added value and allow the assess the overall performance of the geothermal system. However, monitoring data can be incomplete or unavailable, which can limit the accuracy of the evaluation. Moreover, the process of obtaining detailed monitoring data proved to be very time-consuming.

Specific software exists to design a closed loop system (e.g. EED and GHEtool). These software packages allow to compute fluid temperatures of the Borehole Heat Exchanger (BHE) field in function of the ground thermal properties, the BHE field geometry, the monthly/hourly/… heat and cold load profiles and many other parameters. Fluid temperatures computed by design software can be compared with the monitoring data, e.g., to analyse long-term behaviour or assess the influence of differences in design and real thermal loads.

The 3 case studies are extensively discussed in separate reports. In the next paragraphs, the case studies are briefly presented.

4.4.2. Monitoring of an office building in the Brussels city centre (case 1)

4.4.2.1.Production and design of the geothermal system

A part of the heat and cold demand of the studied office building in the Brussels city centre is delivered by a closed loop geothermal system. The borehole heat exchanger (BHE) field is connected to a heat pump (440 kW) and a plate heat exchanger (155 kW). The geothermal energy is used for the heat/cold

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[1] Building details are confidential

roofs in the offices. Two condensing boilers and one cogeneration unit supply the other part of the heat demand. The other part of the cold demand is generated by free chillers and two cooling towers.

The cold and heat production of the BHE field was analysed for the last six years (2017-2022). Figure 25 shows the annual production of the geothermal system. The cold and heat energy production are clearly unbalanced (ratio between cold and heat energy production about 3.5% for the entire monitoring period). The design of the BHE field was based on a ratio of 50%, i.e., 302 MWh for cooling and 600 MWh for heating. While the actual heat production is of the same order of magnitude as the design values (although systematically lower, about 66% of the design value), the actual cooling production is much lower (only 5% of the design value).

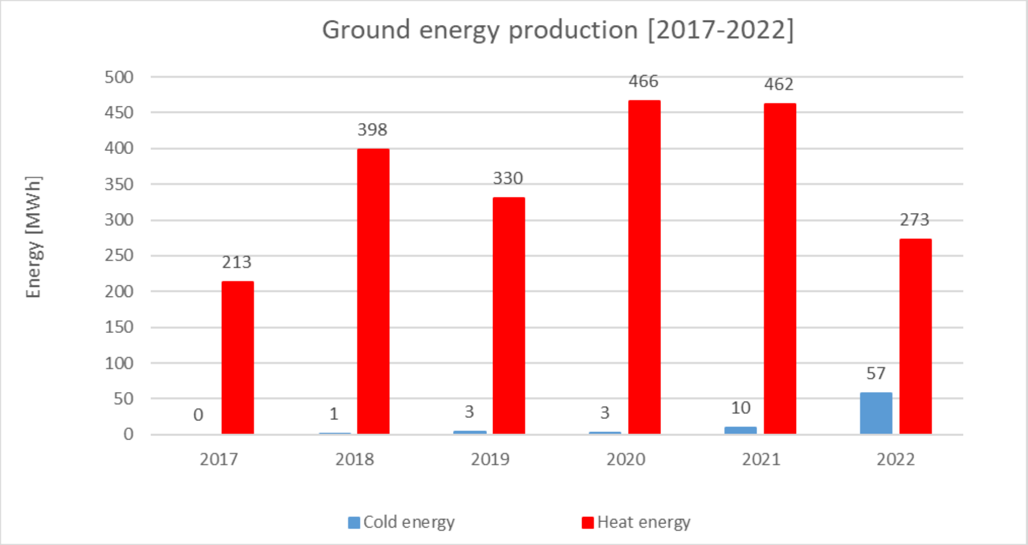


Figure 25 : Geothermal energy production per year for the office building in the Brussels city centre.

4.4.2.2. Control system

The control system for heating and cooling of the building is based on two rules. First, when the outdoor temperature drops below 12°C, the valve to the heat pump is opened and vice versa, the valve to the plate heat exchanger (free geocooling) is closed when the outdoor temperature is higher than 12°C. The second rule forces the free geocooling to be stopped under the following conditions:

- Summer period (from April 1 to September 1): if the fluid temperature coming from the BHE is higher than 14°C, free geocooling production is stopped for the rest of the summer
- Winter period: (from September 1 to April 1): if the temperature of the water coming from the BHE is below 4°C, the geothermal heat production is stopped for the rest of the winter period

The monitoring data shows that free geocooling is only functioning for a very short time period at the start of the summer (see Figure 26). Then, the fluid temperature coming from the BHE field reaches the temperature limit of 14°C and free geocooling is stopped for the rest of the summer. More specifically, Figure 26 shows that free geocooling via the plate heat exchanger functioned mainly during May and then stopped functioning for the rest of the summer.

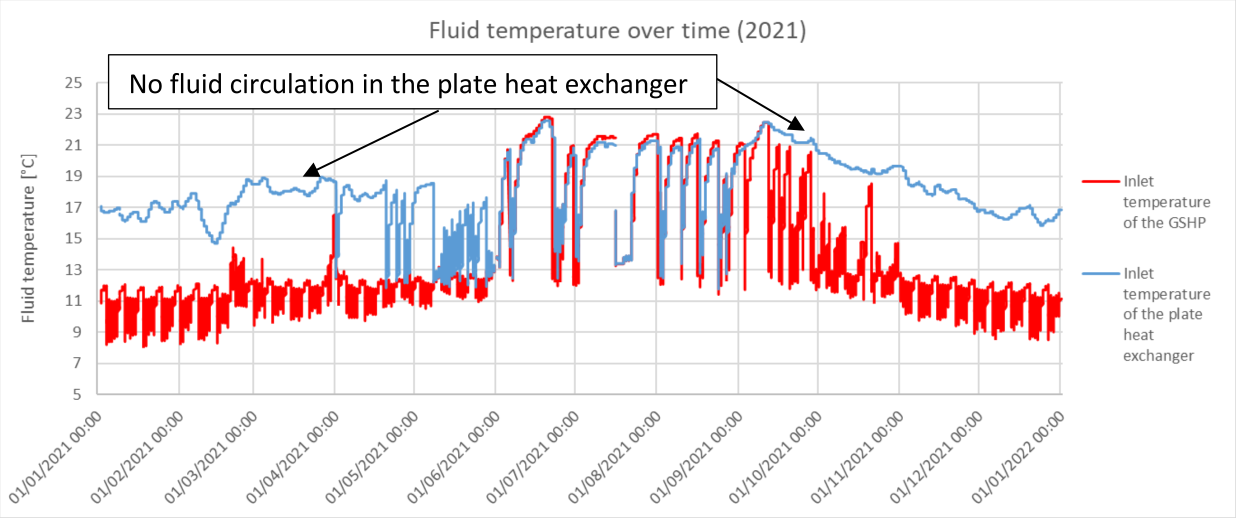


Figure 26 : Fluid temperature at the inlet of the GSHP and the plate heat exchanger during 2021

In order to increase the very limited cold production (less than 5% of the design value) and to further increase the heat production by the geothermal system, the following solutions have been proposed to the building manager:

- Increase the free geocooling temperature limit to 15 or 16°C instead of 14°C
- Increase the allowed temperature sent to the warm roofs
- Couple the GSHP with other installations than the ceilings to increase the heating demand
- Use the GSHP in winter to preheat the water of other heat production units

The main idea here is to produce more heat in winter (and fully exploit (or “exhaust”) the available heat reservoir) so that the ground temperature at the start of the summer is lower and thus the free geocooling potential larger. During winter, fluid temperatures remain rather high, which means that the heating potential is much larger than actually exploited. Figure 26 and Figure 27 show the inlet temperature of the GSHP for 2021 and 2022 which is always higher than about 8°C during the heating season.

In consultation with the building manager, it was decided early 2022 to increase the summer setpoint to stop the free geocooling from 14°C to 16°C. No other modifications were applied, mainly due to practical reasons. The effect of changing the free geocooling setpoint on the cold energy production is shown in **Error! Reference source not found.**. Annual cold production increased from 10 MWh in 2021 to 57 MWh in 2022. The plate heat exchanger functioned until August (versus May for 2021), which can be observed in the inlet temperature evolution during 2022 (**Error! Reference source not found.**).

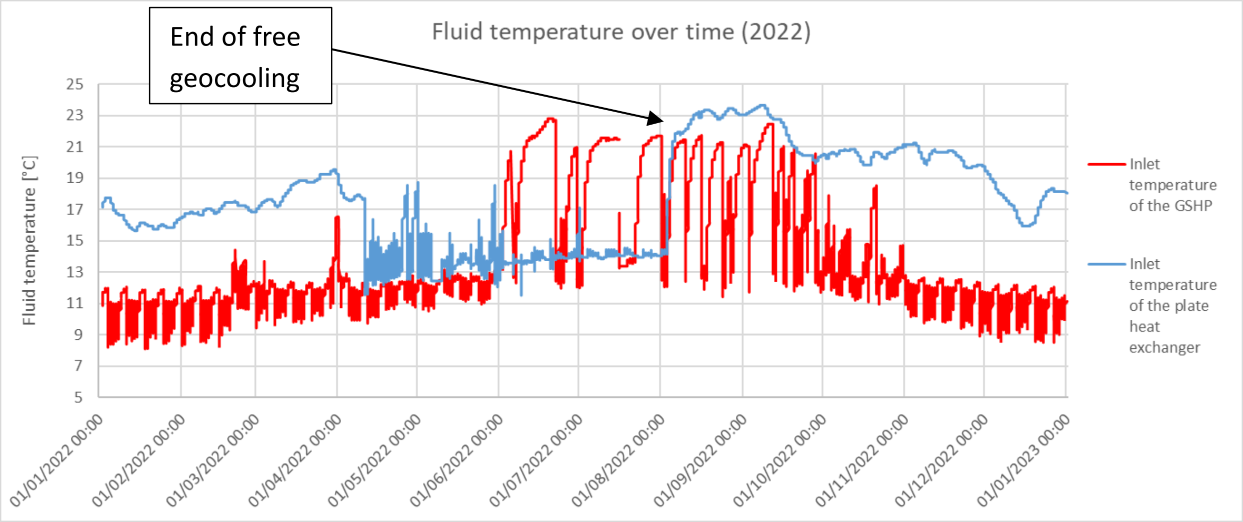


Figure 27 : Fluid temperature at the inlet of the GSHP and the plate heat exchanger during 2022

4.4.2.3.Numerical study and comparison with the available data

The geothermal system is modelled with the Earth Energy Designer (EED) software to better understand the functioning of the geothermal system and evaluate the behaviour of the system in the future. The parameters used in this study were globally the same as those used for the design. The ground parameters were based on the available TRT results.

The fluid temperature reported by EED is the mean fluid temperature (mean of inlet and outlet temperature) at the end of each month. In order to compare the simulation results with the monitoring data, the temperatures in the monitoring data are evaluated as follows: in months where the heating load is higher than the cooling load, the lowest fluid temperature during that month is retained. When the cooling load is higher than the heating load, the highest fluid temperature during that month is used.

The building manager shared the available monitoring data via Excel sheets. These sheets contain the timestamp, the inlet and outlet temperature at the heat pump and at the plate heat exchanger and the status of different pumps. The status of the pumps allows to determine whether the heat pump or the plate heat exchanger (or both) is (are) functioning.

The operational temperatures are compared with two scenarios in EED based on a mean monthly load profile (period 2017-2022) and a ‘maximum’ load profile (energy demand profile of 2022 after setpoint modification). The 2 scenarios are respectively listed as “Tf with real base load (mean, EED)” and “Tf with real base load (2022, EED)” in the results. This approach is chosen as the EED software only allows to define 1 monthly load profile that is repeated every year during the given simulation period. The objective is to evaluate numerically the impact of the free geocooling setpoint (increased to 16°C instead of 14°C) on the (long term) behaviour of the BHE field.

Figure 28 and Figure 29 highlight the results for both scenarios. The grey curve are the measured temperatures, the yellow curve is the simulated fluid temperature for the base load and the blue and red curves are the simulated temperatures taking into account peak loads. Measured and calculated fluid temperatures correspond rather well. For scenario 1, the measured fluid temperatures are higher than the calculated maximum temperature (blue curve) during the summer of 2022 as the real free geocooling production is much larger than average during 2017-2022 due to the control modifications. For scenario 2, the measured fluid temperatures (grey curve) correspond better with the maximum and minimum temperature curves resulting from the simulations (blue and red curves).

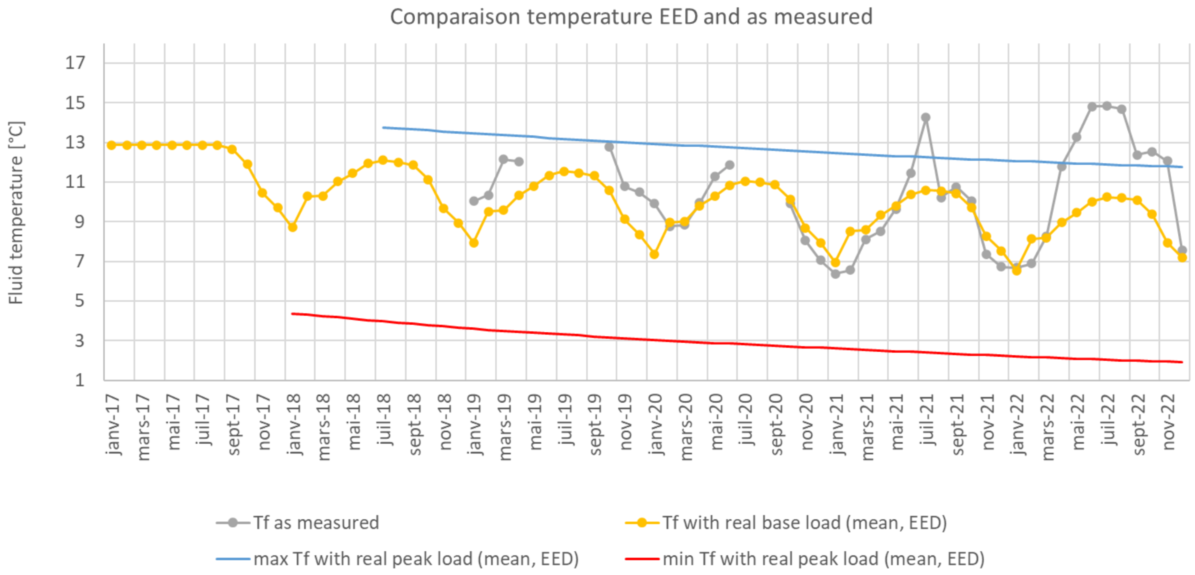


Figure 28 : Comparison of the calculated temperature with EED (based on the mean monthly production during 2017-2022) and the fluid temperature as measured

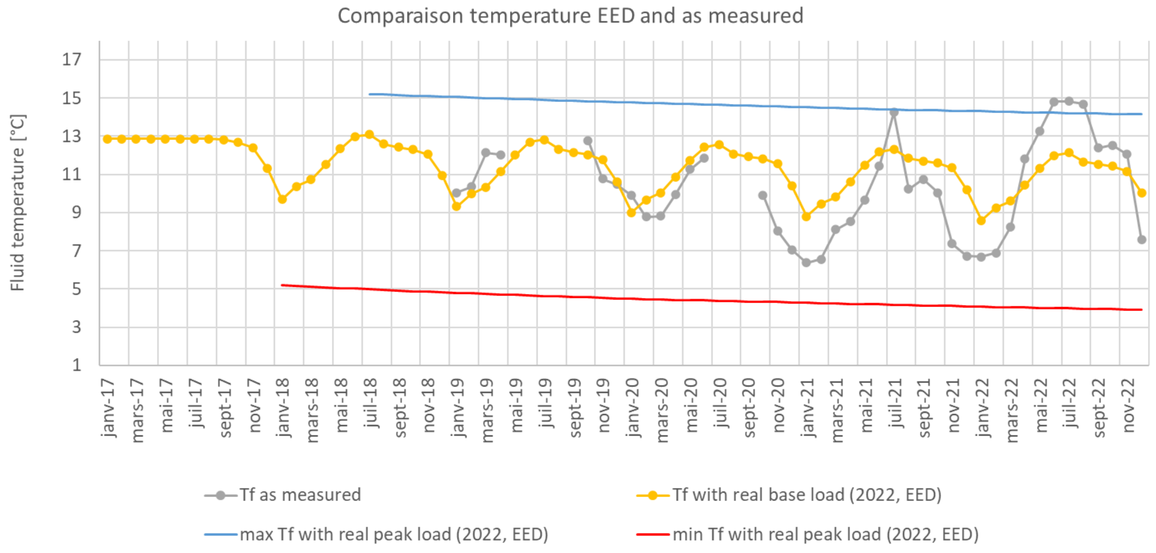


Figure 29 : Comparison of the calculated temperature with EED (based on the monthly energy profile of 2022) and the temperature as measured

Now that it has been demonstrated that the functioning of the geothermal system of the building can be simulated rather well, we can investigate the future behaviour over a larger timescale (e.g., over the next 50 years). This allows to estimate the impact on the ground and fluid temperature and to evaluate the functioning of the current system over a larger timescale.

Figure 30 and Figure 31 show the fluid temperature evolution over the next 50 years for scenarios 1 and 2. For scenario 1, the fluid temperature would decrease significantly over time due to the unbalance between the cold and heat production. The simulations show minimum fluid temperatures below 0°C over time (light red curve), while the minimum design fluid temperatures were set at 0°C (dark red curve). For scenario 2, the fluid temperature will stay between the design temperature limits. However, the potential of the geothermal source is not fully exploited.

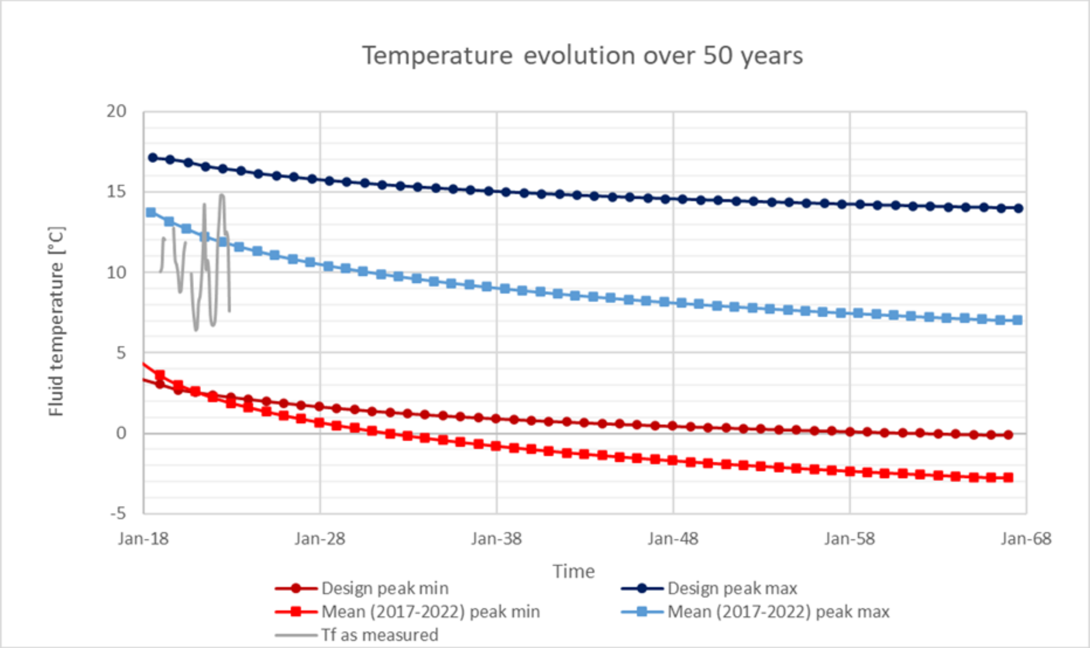


Figure 30 : Fluid temperature calculated for the next 50 years based on the load profile of the first scenario (mean load profile for 2017-2022).

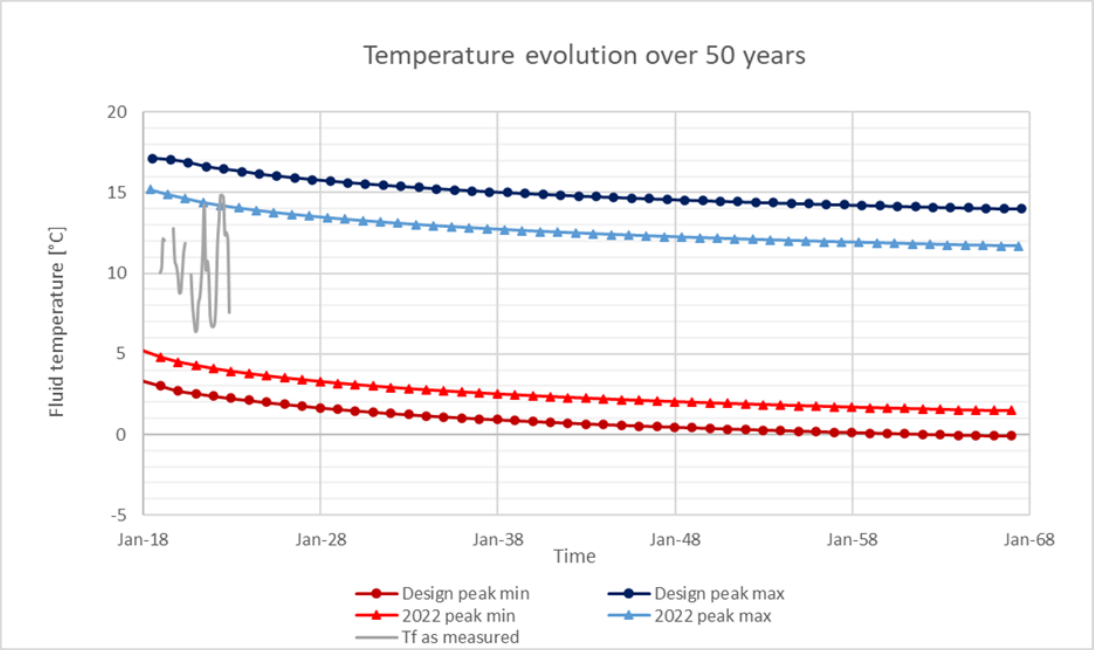


Figure 31 : Fluid temperature calculated for the next 50 years based on the load profile of the second scenario (load profile of 2022).

4.4.3. Office building of AGC (case 2)

4.4.3.1. Introduction

The new office building of AGC in Louvain-la-Neuve was finished in 2014. The heat demand and a part of the cold demand of the building is delivered by a closed loop geothermal system. This geothermal system consists of 42 borehole heat exchangers (BHE), each 75 meters long and spaced by 10 meters. It was installed next to the building (Figure 32).

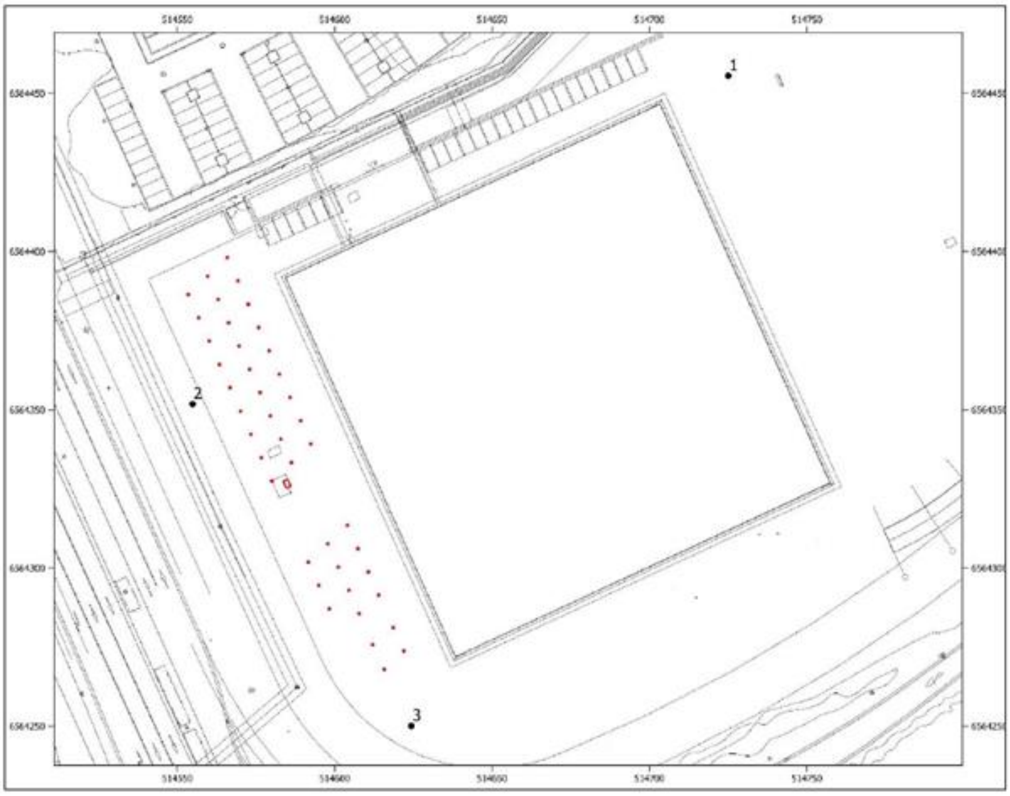


Figure 32 : Plan view of the AGC building and the location of the boreholes of the BHE geothermal field next to the building.

4.4.3.2.Production of the geothermal system

The cold and heat production of the BHE field was analysed for the last eight years (2015-2022). During this period, no data is available between February 2018 and August 2019. Figure 33 shows the annual production of the BHE field. The black dashed curve on Figure 33 is the cumulative energy (energy extraction for building heating is negative, energy injection for building cooling is positive). Figure 34 shows both cumulative heat and cold production of the BHE field. These figures show that cold and heat energy production are well balanced for the BHE field.

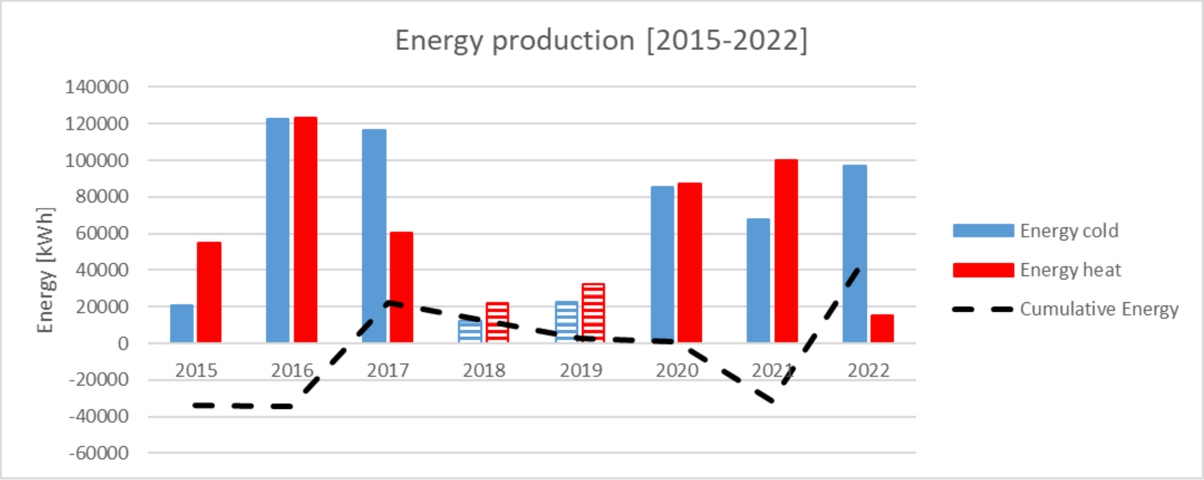


Figure 33 : Annual geothermal energy production. "Energy cold" is injected energy for building cooling, "energy heat" is extracted energy for building heating. Note that data is missing for the period between February 2018 and August 2019.

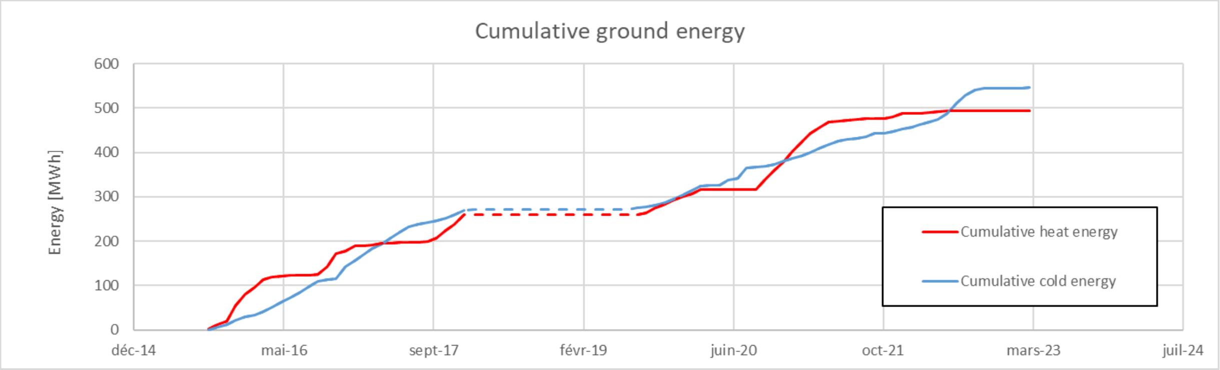


Figure 34 : Cumulative cold and heat energy . Note that data is missing for the period between February 2018 and August 2019.

4.4.3.3.Numerical study and comparison with monitoring data

The monitoring data is compared with the results of numerical simulations with the EED software package. Thermal soil parameters are deduced from in situ TRT and ETRT tests, that were executed in the past (see for example Figure 35). The average monthly heat and cold production during the studied period (2015-2022) is used as the load profile. For this analysis, only the base profile is taken into account because no information about the peak loads is available. Figure 36**Error! Reference source not found.** shows the monthly load profile of the scenario used for the analysis.

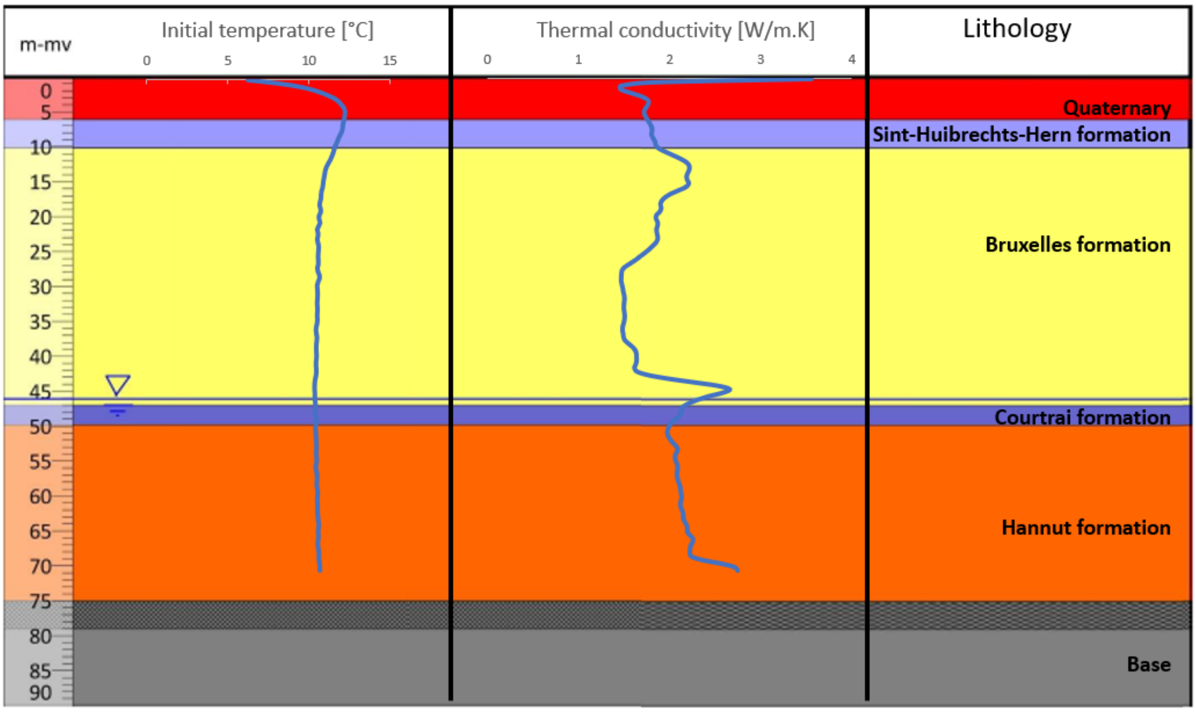


Figure 35 : ETRT results (temperature and thermal conductivity) with lithology as background.

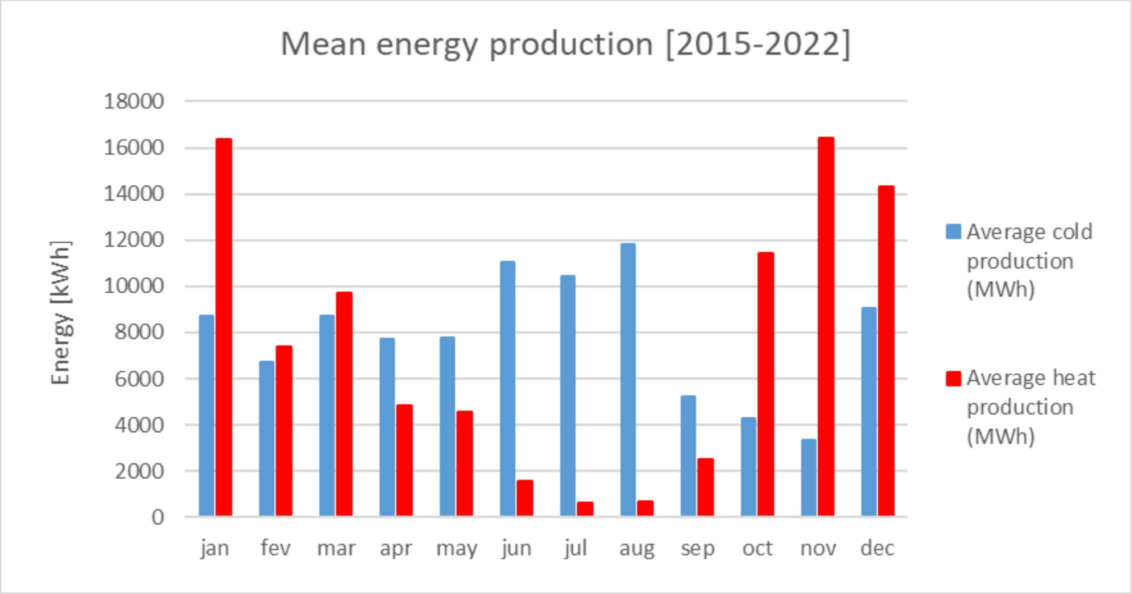


Figure 36 : Applied monthly load profile used for the EED analysis based on the average production (2015-2022).

4.4.3.4. Results

Figure 37 shows an overview of the operational monitoring data of the geothermal system (fluid temperatures and energy production). The red and blue curves are the average of the inlet and outlet temperatures of the system measured during heat and cold production, respectively (provided by the

IFTECH monitoring reports). The grey curve is the average of these two curves. The bars in Figure 37 show the monthly heat and cold energy production. This illustrates how the fluid temperature changes with cold and heat energy production. When cold is produced in summer, the fluid temperature increases and vice versa during heating in winter. This is foremost pronounced during November and December 2016. These 2 months show respectively a high heat and cold production and thus a quick decrease and increase in the fluid temperature. Figure 38 shows the monthly average heat and cold production and the resulting simulated fluid temperatures by EED (yellow curve). The dashed curves (red, blue and grey) are the same as those presented on Figure 37. The measured (grey curve) and calculated (yellow curve) fluid temperatures correspond rather well.

Now that it has been demonstrated that the functioning of the geothermal system of the building can be simulated rather well, it is interesting to investigate the future behaviour over a larger timescale (e.g., over the next 50 years). This allows to estimate the impact on the fluid temperature and to evaluate the functioning of the system over a larger timescale. Figure 39 shows the fluid temperature evolution over the next 50 years for the same yearly load profile as used in Figure 38 (mean monthly load based on the period 2015-2022). The temperature stabilizes quickly after a slight temperature increase during the first few years after the start of system operation, with the increase being less than 0.5°C.

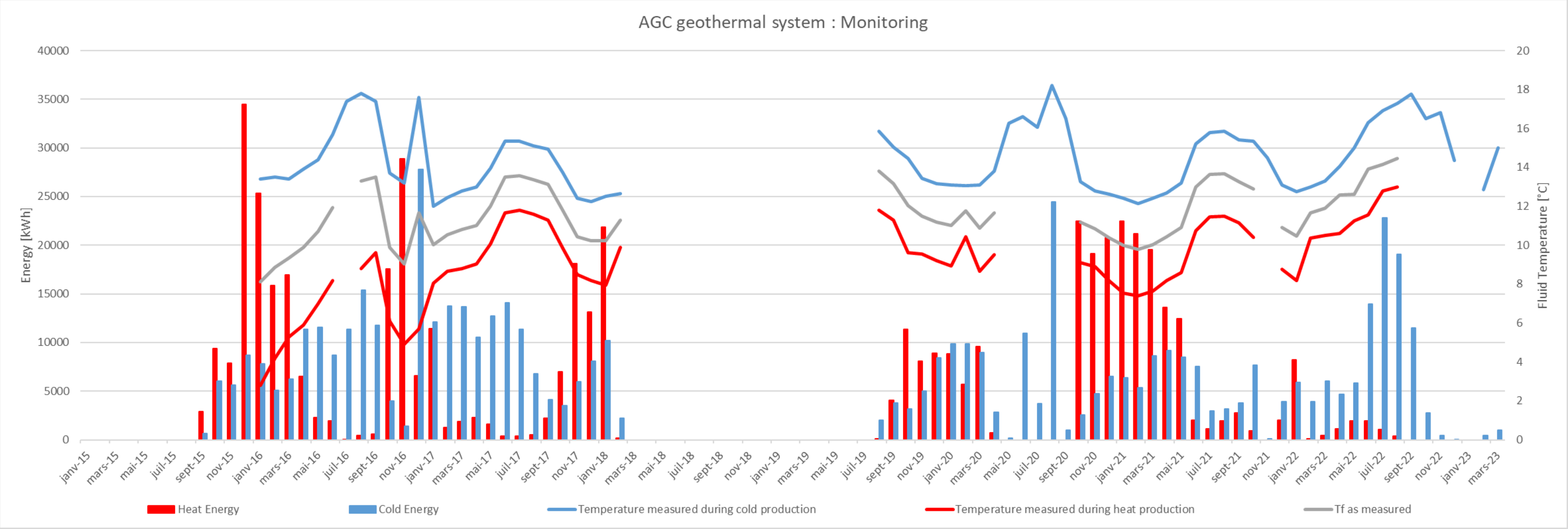


Figure 37 : Overview of the operational monitoring data of the geothermal system since 2015.

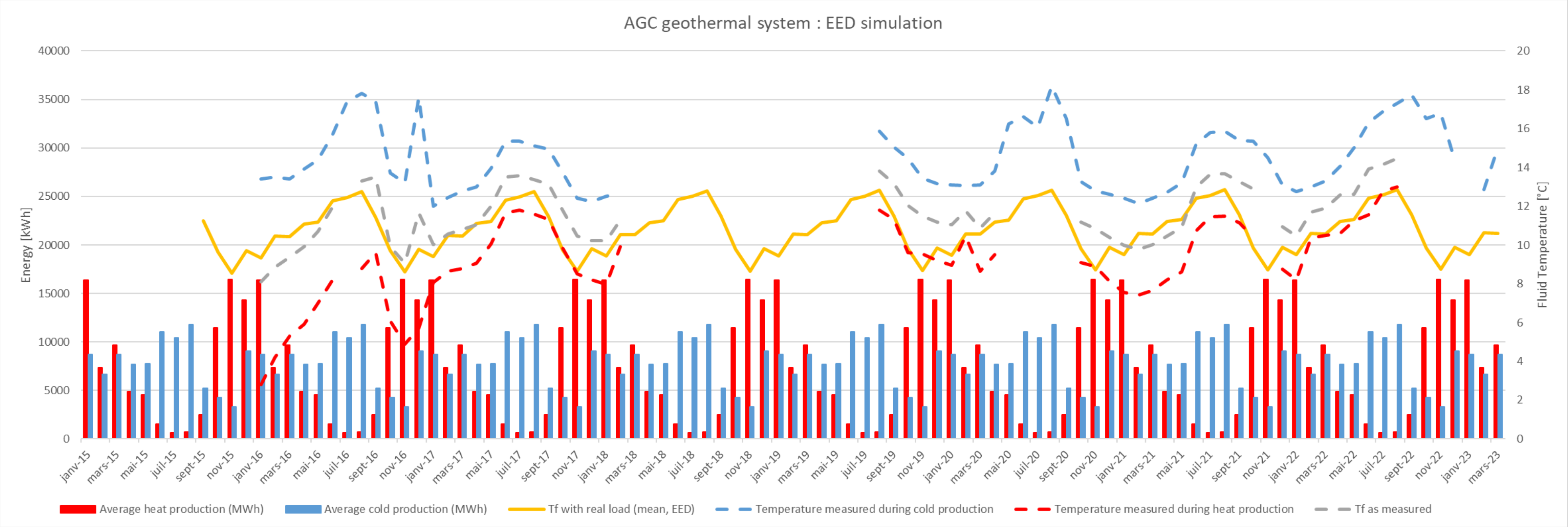


Figure 38 : Overview of the average monthly energy provided by the BHE system since 2015 and the resulting computed fluid temperature.

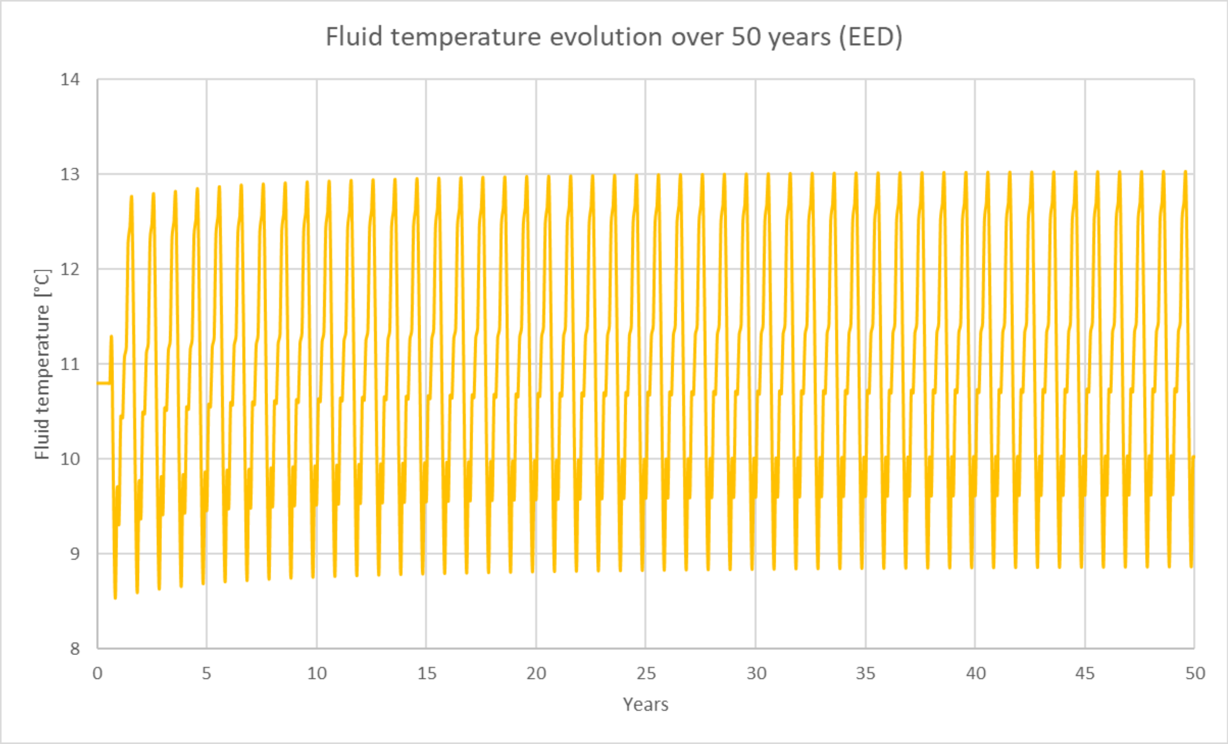


Figure 39 : Mean fluid temperature calculated by EED for the next 50 years based on mean load profile for 2015-2022

4.4.4. Gare Maritime building (case 3)

4.4.4.1. Introduction

The renovation of the Gare Maritime building on the Tour and Taxis site in Brussels was finished in 2020. Nextensa, the owner and property developer, made the choice to heat and cool the building units inside the building by means of a centralized open geothermal system or Aquifer Thermal Energy Storage (ATES) system that is connected to the individual heat pumps of the building units.

An ATES system or open geothermal system requires a suitable aquifer, i.e. a permeable soil layer saturated with groundwater, into which at least two thermal wells are installed (a warm and cold well). The application involves pumping and storage of water into the aquifer. Figure 40 illustrates the principle. During winter months, groundwater is pumped from the warm wells. After the water has been used for heating by means of heat pumps, the colder water is re-injected and stored in the aquifer via the cold wells. During summer months, the functioning of the system is switched. Groundwater is then pumped from the cold wells. After the water has been used for cooling (mostly passive cooling by means of plate heat exchangers), the warmer water is re-injected and stored in the aquifer via the warm wells.

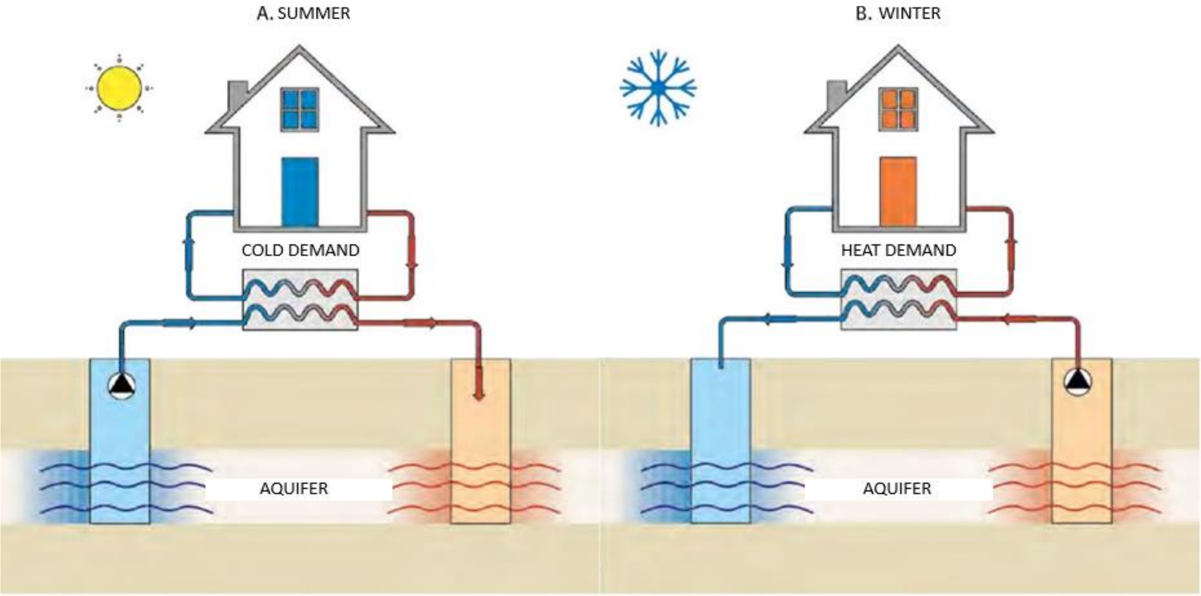


Figure 40 : Principle of the functioning of an ATES system (source: Buildwise Innovation Paper 24).

4.4.4.2.Gare Maritime ATES system

The ATES system of Gare Maritime consists of 10 boreholes with depths between 130 and 200 meters (5 warm wells and 5 cold wells). Note the large variability of the capacity of the wells (see Table 1). The wells are drilled inside the building prior to/during renovation (see Figure 41 for the location of the cold and warm wells). The bedrock is found at a depth of about 60 to 74 meters. Figure 42 shows the variability of the top of the bedrock on the site and the location of the wells.

The wells are always controlled in pairs (indicated by the colour coding in Table 1). The pair with the largest capacity is always activated first to ensure the hydraulic stability of the system (i.e., warm well 3 and cold well 3). Other pairs of wells are added if required to satisfy the demand. If one pair is used, the hydraulic flow from the pumping well to the corresponding injection well is known. When multiple pairs are active, the re-injection flow is not controlled per well pair. The well pairs feed into a buffer volume to manage simultaneous heat and cold demand.

Table 1. Overview of the wells, their depths and pumping capacities. The wells are connected in pairs with comparable pump capacity (indicated by the colour coding).

Borehole	**Well**	**Depth (m)**	**Well capacity (m^3/h)**	**Total capacity**
1	WW1	150 m	15	180 m^3/h
10	WW2	151 m	45	
5	WW3	139 m	75	
3	WW4	150 m	15	
4	WW5	150 m	30	
2	CW1	200 m	15	180 m^3/h
6	CW2	166 m	15	
8	CW3	130 m	75	
9	CW4	148 m	45	
7	CW5	160 m	30	

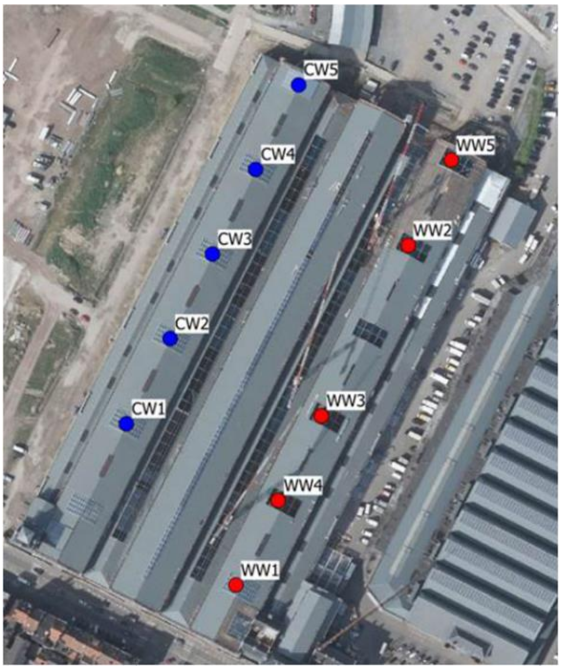


Figure 41 : Location of the 5 cold and 5 warm wells in the Gare Maritime building.

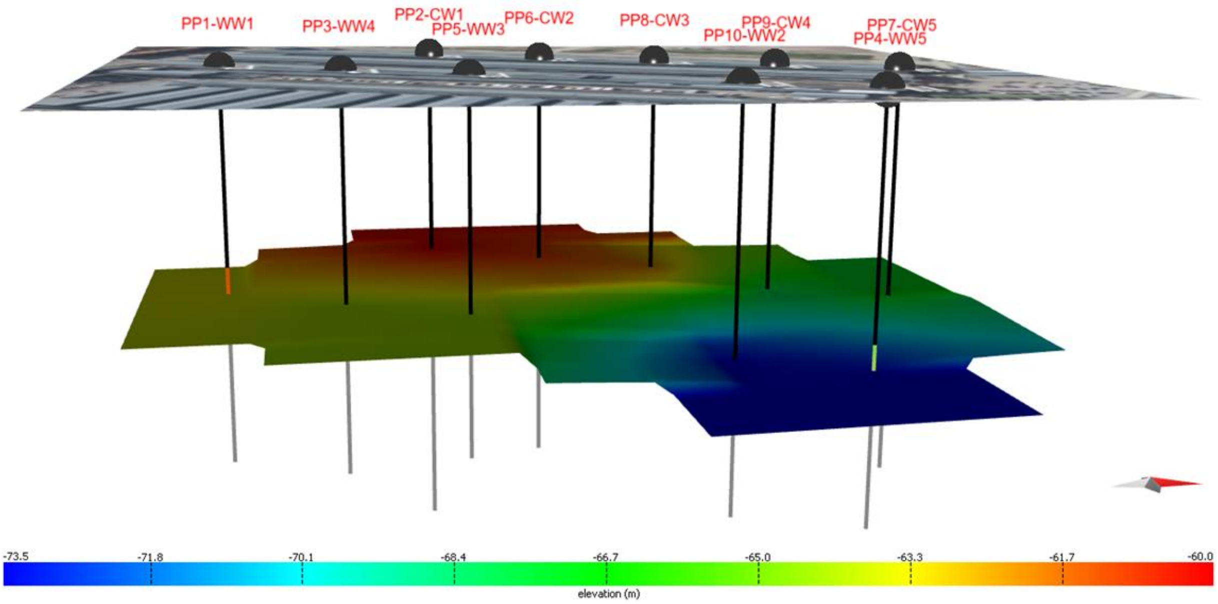


Figure 42 : Top of the bedrock encountered on the site and location of the 10 wells at Gare Maritime.

4.4.4.3.Analyse of the monitoring data of Gare Maritime

The functioning of the ATES system is controlled centrally. Energy flows are monitored (heat and cold extraction from the ATES system) and each well is provided with a temperature and groundwater level sensor. This sensor is located in the wells and measures the groundwater temperature at this location.

The cold and heat production of the ATES system was analysed for a period of 2 years (April 2022 – April 2024). Figure 43 shows the total energy provided by the system since its start. The cold and heat energy provided by the aquifer is respectively 1 622 and 1 008 MWh. Figure 44 shows the cumulative energy evolution.

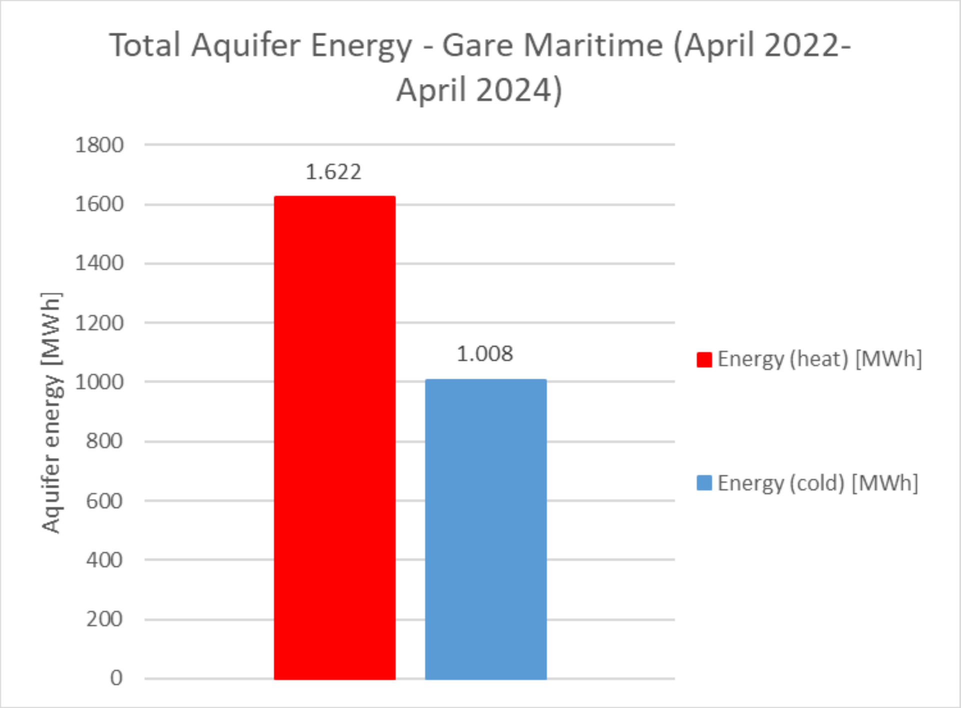


Figure 43 : Total geothermal energy provided since the start of the system

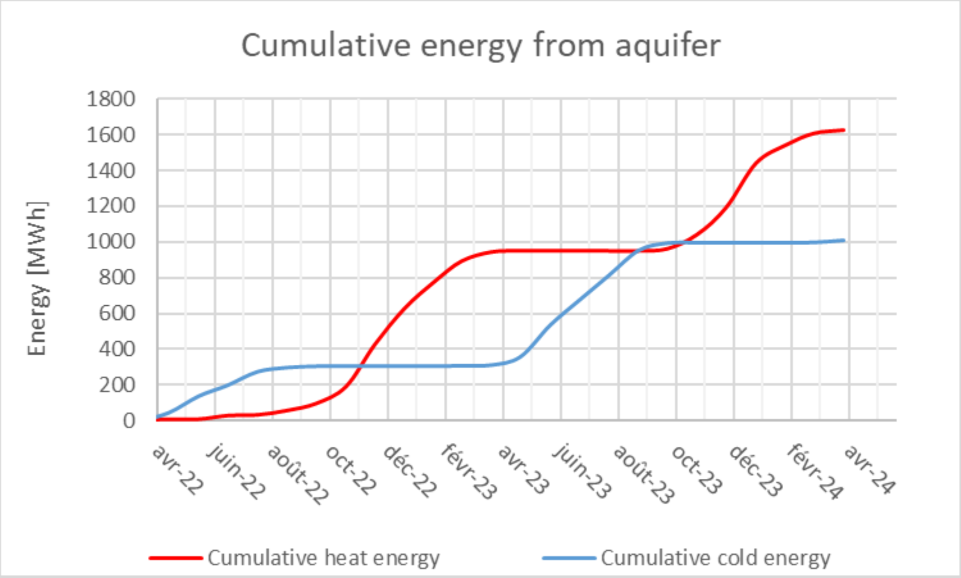


Figure 44 : Cumulative heat and cold energy extracted from the aquifer during the first 2 years of operation

An overview of the fluid temperatures and extracted energy for the 2 years of operation is illustrated in Figure 45. The red and blue curves are respectively the measured fluid temperatures in the warm and cold wells based on the average of the monthly mean of each heat/cold wells. The graph also shows the monthly energy provided by the aquifer. It can be observed how the mean temperature of the warm wells increases during summer, as heat from the building is stored in the aquifer. During winter, the mean temperature in the cold wells decreases as the heat pumps extract energy from the groundwater coming from the warm wells, before its stored in the cold wells. The red and blue dashed curves show the measured fluid temperature in the warm and cold wells based on the average of the monthly maximum of all warm/cold wells. The red and blue dotted curves show the measured fluid temperature in the warm and cold wells based on the maximum/minimum of the monthly maximum/minimum of all warm/cold wells. These curves correspond to the maximum and minimum monthly fluid temperature recorded by the system. The extreme fluid temperatures in the warm and cold wells reach respectively 16°C and 8°C.

To further understand the behaviour of the ATES system, a first zoom is made on the data of April 2023 (Figure 46 & Figure 47). During this month, the building had a higher heating demand (51 MWh) than cooling demand (3.5 MWh). Thus, the system mainly pumps water from the warm wells (water level drops) and reinjects it into the cold wells (water level raises, Figure 48 & Figure 49). Groundwater is extracted from the warm wells at a temperature of about 12°C and reinjected into the cold wells at about 8°C. The operating periods are also clearly visible on these graphs, with less or no energy demand during the weekends.

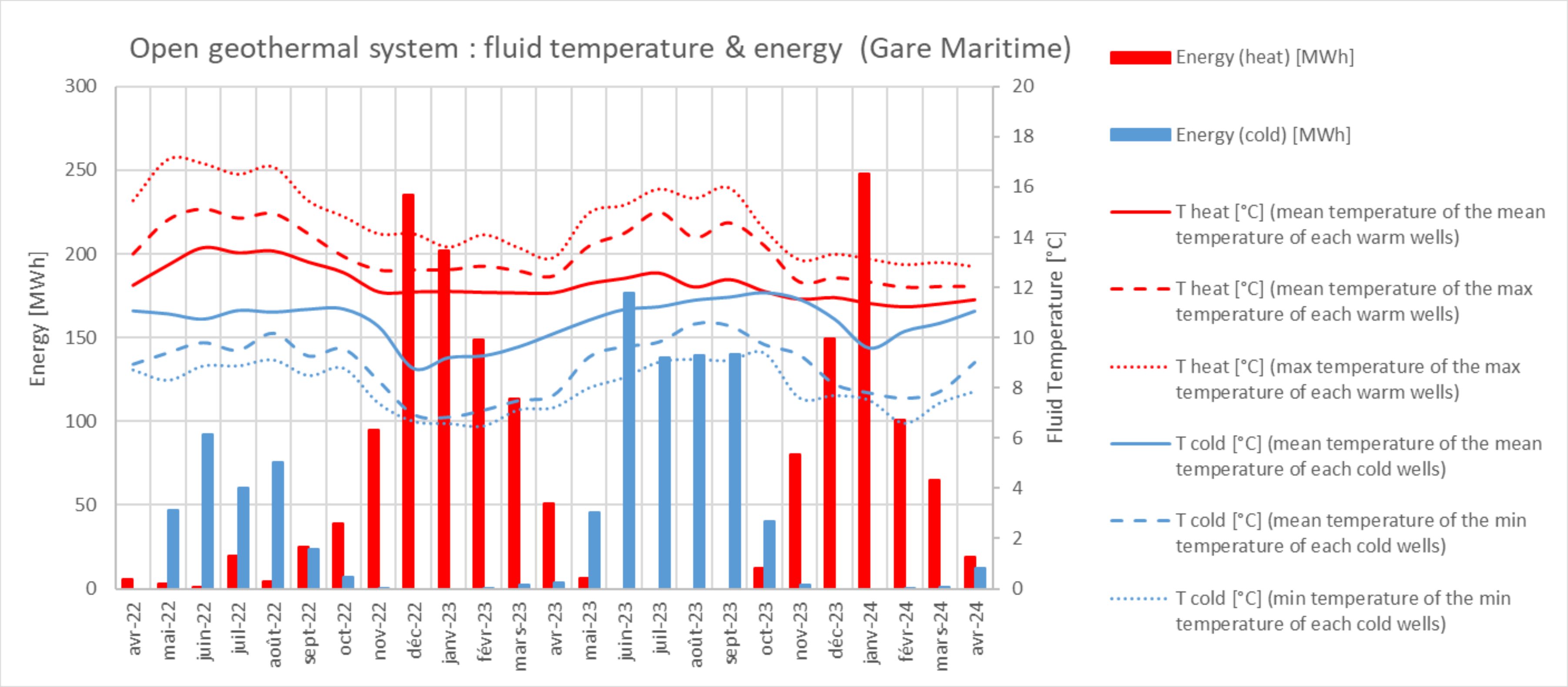


Figure 45 : Overview of the operational data of the open geothermal system (extracted energy and groundwater temperature)

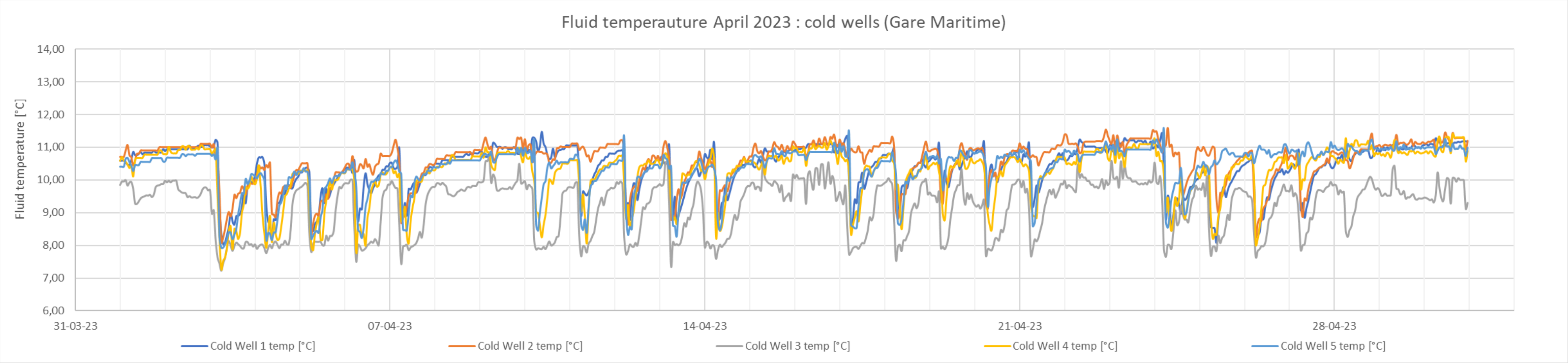


Figure 46 : Groundwater temperature in the cold wells for April 2023

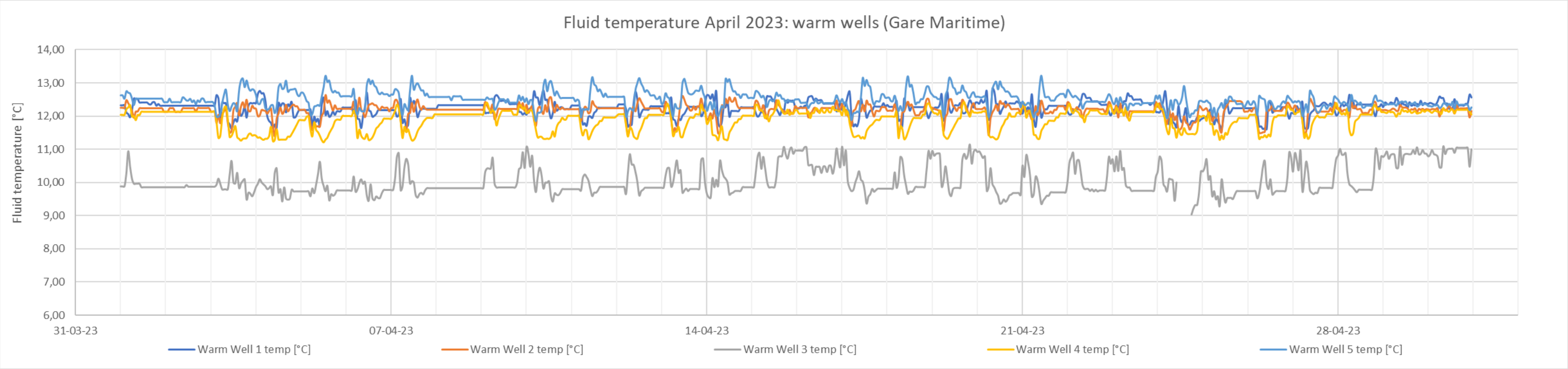


Figure 47 : Groundwater temperature in the warm wells for April 2023

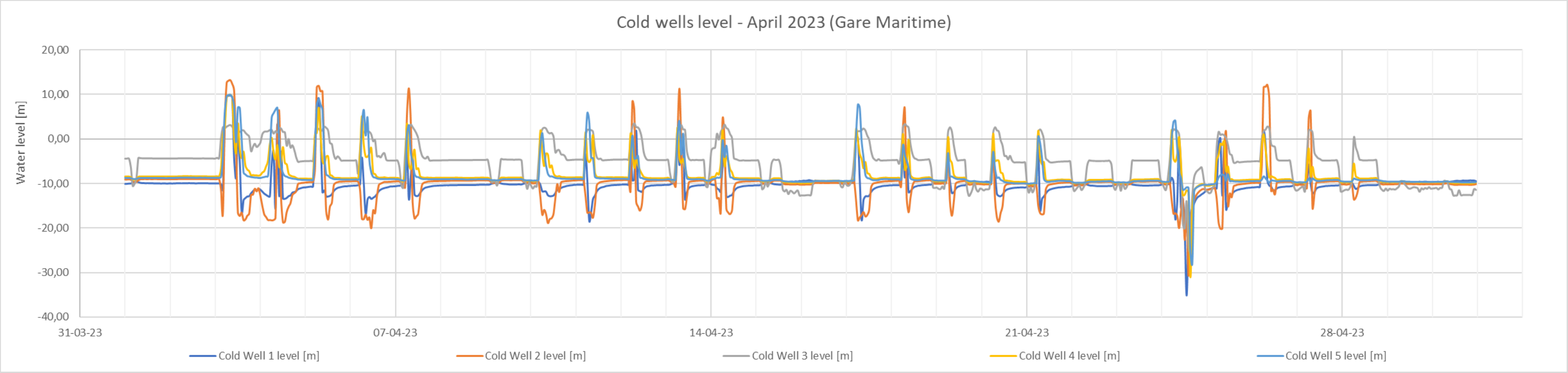


Figure 48 : Groundwater level in the cold wells for April 2023

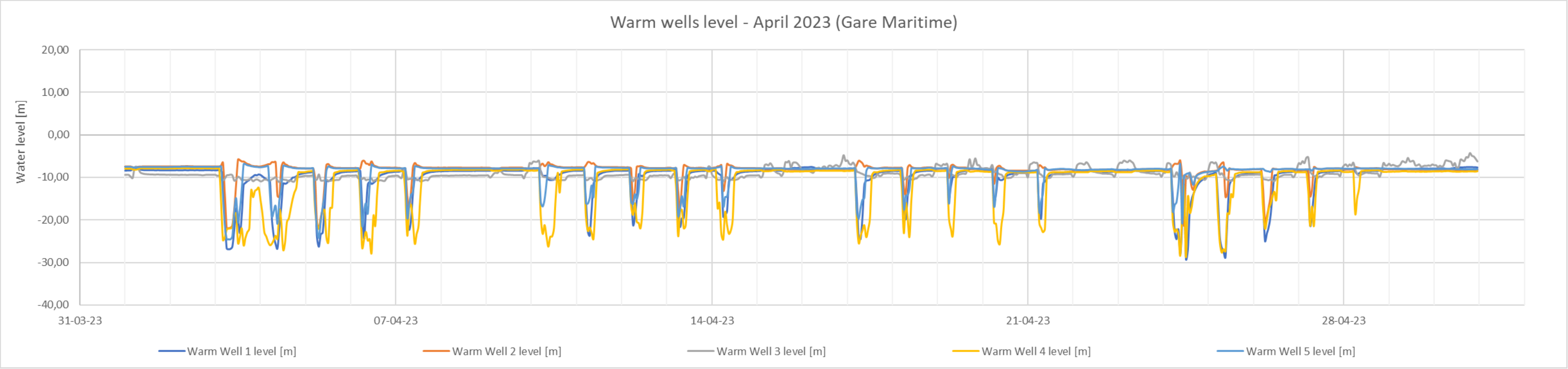


Figure 49 : Groundwater level in the warm wells for April 2023

Next, it is interesting to focus even more, e.g., on a week of monitoring data during only heating/cooling demand. For this analysis, the data of only one well pair is shown; cold well 1 and warm well 1 (winter period) and cold well 5 and warm well 5 (summer period). For simplicity, the following analysis disregards the fact that when multiple well pairs are active, the reinjection flow is not controlled (as explained in Section 4.4.4.2).

For the winter period, the week from February 13 to February 20, 2023, has been selected. During that period, there was only heating demand. Groundwater is pumped from the warm well (water level drops) into the cold well (water level raises) from 6 a.m. to 12 p.m (Figure 50). The temperature of the warm well remains rather constant at about 12°C (Figure 51). The injection temperature in the cold well is at about 8°C (minimum) at the operation start every morning and raises slightly during the day.

The selected period during summer starts at August 8 until August 15, 2023. During that period, there is a limited heat demand of 4 MWh and a cooling demand of 75 MWh from the buffer. Figure 52 shows the groundwater level in both cold and warm wells 5 (groundwater level at rest is at about -8m). The groundwater temperature in both wells is shown in Figure 53. During this period, groundwater is mainly pumped from the cold well to the warm well. Some days, flow direction is switched in the morning (6-9 a.m.) to compensate for some heat demand. The temperature of the cold well remains rather constant at about 11°C, except during the re-injection period in the cold well (6-9 a.m.) where the temperature reaches 12°C. The injection temperature in the warm well is at about 16°C (maximum) at the afternoon and decreases slightly during the night.

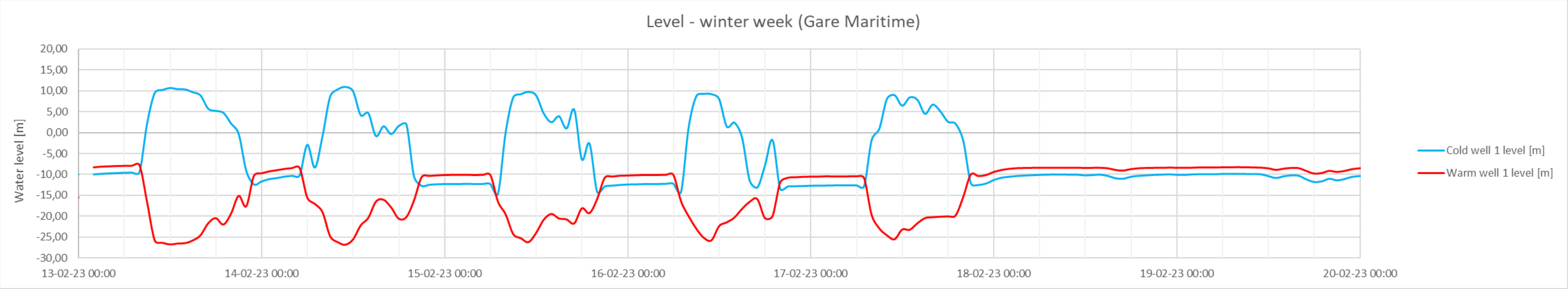


Figure 50 : Zoom on a week during winter for the groundwater level in cold and warm well 1

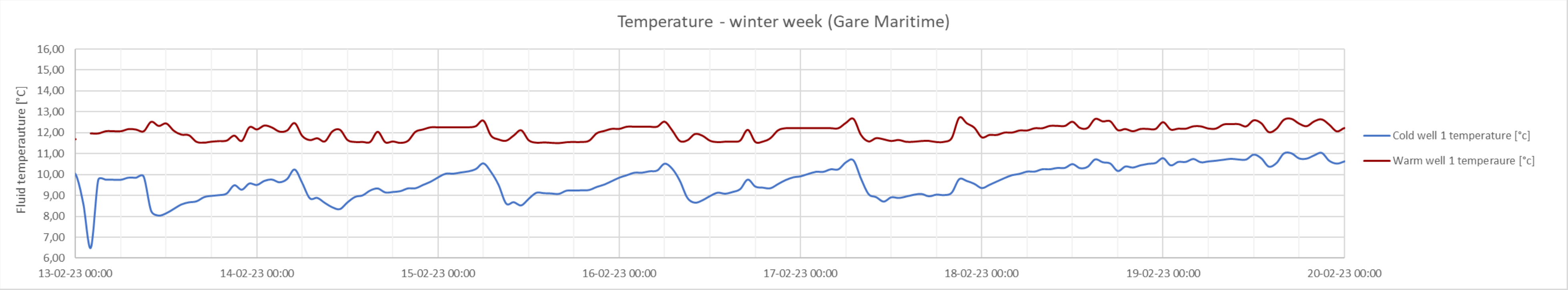


Figure 51 : Zoom on a week during winter for the temperature in cold and warm well 1

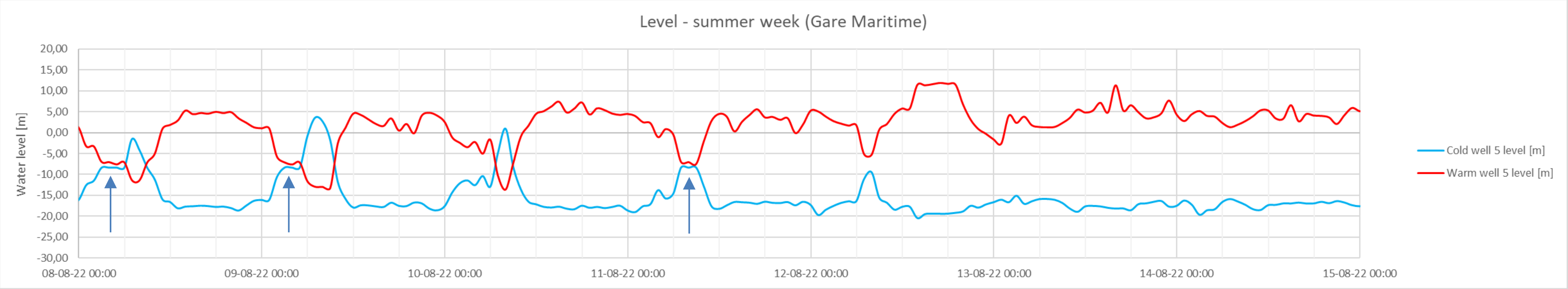


Figure 52 : Zoom on week during summer for the groundwater level in cold well 5 and warm well 5. The arrows indicate periods without pumping.

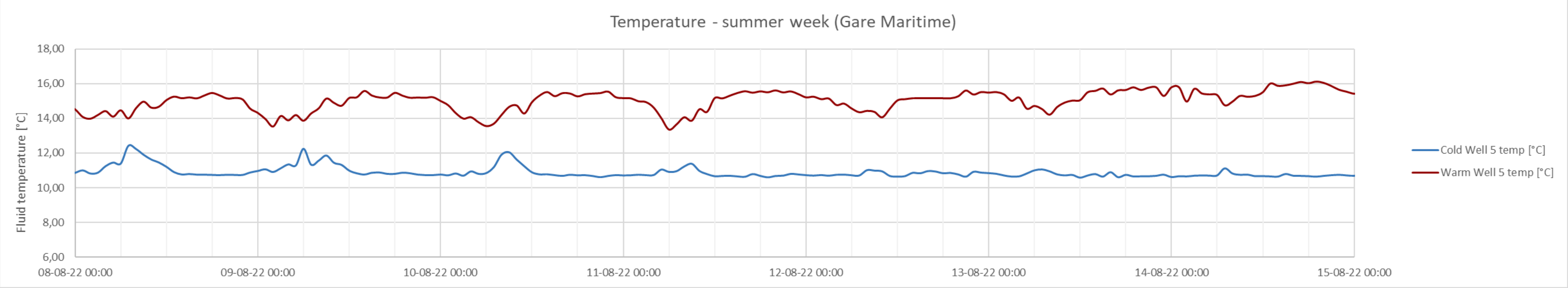


Figure 53 : Zoom on a week during summer for the groundwater temperature in cold well 5 and warm well 5

4.4.5. Conclusions

The operational monitoring data of two closed geothermal system (office building and office building of AGC) and one open geothermal system (Gare Maritime building) were analysed in the framework of this project. The presented figures clearly demonstrate the working principle of both closed loop and open loop geothermal system.

A closed-loop geothermal system operates on an energy extraction/injection cycle; the building is heated in winter (heat extracted from the ground) and cooled in summer (heat injected into the ground). Thermal equilibrium is achieved when the average temperature of the carrier fluid is stable over the seasons. A well-designed system seeks thermal equilibrium. This thermal equilibrium can be achieved by balancing the heat and cold production. However, this depends on many parameters such as the BHE field geometry, the thermal ground parameters, etc. A certain imbalance can be tolerated within a BHE field, but it must be designed accordingly. A well balanced heat and cold production enables correctly seasonal thermal energy storage, offering high efficiency through thermal buffering and ensuring long term performance.

In order to forecast the future fluid temperature evolution, EED simulations were performed over the next 50 years to assess the fluid temperature evolution for the current energy load. Some changes (such as a reduction or increase in the cold/heat production) can be modelled to understand the impact of these measures over the long term. A small change in the control system can have a real impact on the efficiency of the geothermal system.

Unlike traditional HVAC systems, geothermal systems require careful monitoring and close follow-up especially at the start of the system. This allows to react as quickly as possible to poor or undesired behaviour of the system (e.g. if the fluid temperature drops below design values). Flexibility should be considered during the design to allow for future modifications or optimizations. This requires a solid understanding of the system by building managers and/or an expert support.

Especially for the open geothermal system, the available monitoring data allows to better understand the functioning of ATES systems. The data illustrates the principle of ATES systems, consisting of one or more pairs of warm and cold wells, acting as underground thermal seasonal buffers. It is clear that an ATES system requires a well-thought control system and a regular follow-up in order to guarantee its well-functioning. The energy balance between the cold and warm wells should be controlled, monitored and evaluated on the long term (e.g., a period of 5 years) to maintain the well temperatures within the right working range.

In this report the case studies and performed analyses were presented briefly. For more details, we refer to the dedicated Buildwise reports for each case study. Some additional reports are available as well:

- *Buildwise, 2024. Drilling cost assessment of an office building's geothermal system.* The report presents a simplified assessment of the impact of borehole depth on the total drilling cost, based on the building case 1 presented in section 4.4.2. Such a study proves to be quite complex. On the one hand, there is significant variability in drilling costs, which depend on various factors such as the number of boreholes, the depth of the boreholes, the depth of the rock layer, etc. There is insufficient data available to account for all these factors in the drilling cost for the study. On the other hand, the results show that thermal conductivity, undisturbed ground temperature, the balance between heating and cooling demands, etc. play a significant role in the BHE field design.

- *Buildwise, 2024. Geothermal feasibility study for the Ghandi apartment buildings (Molenbeek).* This report addresses the BHE design for the Ghandi apartment buildings based on the energy load profiles for different renovation scenarios. The study shows the effect of the ratio between cooling and heating demand on the BHE design. Investments to reduce coolling demand can have a significant impact on the BHE design and lead to optimizations.
- *Buildwise, 2024. Thermally enhanced grout vs. soil conductivity.* The influence of thermally enhanced grout on the BHE design is investigated, with respect to the soil thermal conductivity. In other words, to which extent is it beneficial for the BHE design to apply a thermally enhanced grout (i.e., a grout with higher thermal conductivity than traditional grouts) in lower conductive soils? This limited study showed that the application of high conductive grouts in lower conductive soils has only limited benefit in terms of BHE design. This benefit is larger for single U loop configurations than for double U loop configurations. The conductivity of most applied grouts in Belgium range between 1.2 and 2.2 W/mK. Within this range the effect of the grout conductivity is less pronounced than for the lowest grout conductivities that have been studied. The final choice of grout type/grout conductivity will probably be an economical question based on the costs of amongst others: single/double U loop heat exchangers, the grout, …, in combination with the corresponding required borehole length.
- *Buildwise, 2024. Impact of the land use and the topography on the ground temperature profile.* Several Enhanced Thermal Response Tests that were carried out in the past showed very important inverse thermal gradients up to depths of 60m and more (Figure 54). This is mainly due the heat island effect of built environments and leads to higher “undisturbed” soil temperatures. These higher temperatures affect the free geocooling capacity of geothermal systems, if they are not taken into account adequately in the geothermal design. This study tried to better understand the phenomena leading to these inverse thermal gradients by analytical and numerical modelling with Plaxis, a Finite Element Modelling software package for geotechnical applications. The effect of topography was studied as well and appears to be limited.

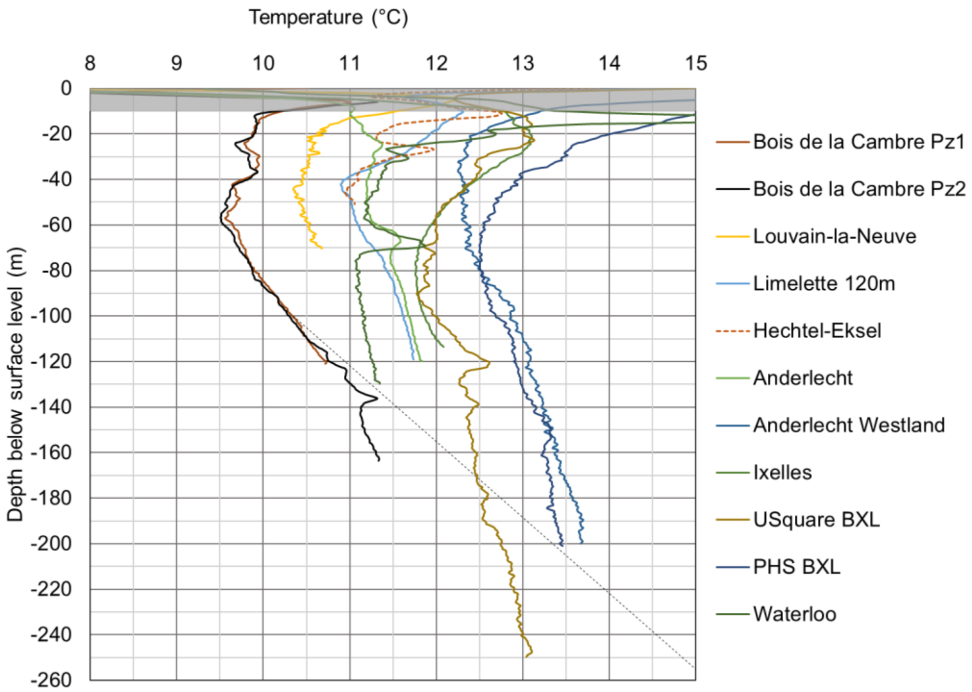


Figure 54. Temperature profiles from the eTRT database. The upper 10m below surface level are greyed out as this zone is influenced by seasonal fluctuations.

Finally, the temperature of a borehole of the BHE field of the Buildwise headquarters in Zaventem was monitored continuously during operation with optical fiber technology. Figure 55 (a) presents the temperature evolution in the borehole at several depths .Figure 55 (b) shows the temperature along borehole depth for some selected timestamps (before operation, during heating demand (lower borehole temperatures), and during cooling demand (higher borehole temperatures)). **Error! Reference source not found.**a and b show 2 zooms on the time evolution during winter and summer, respectively. The operation of the heat pumps/plate heat exchangers can be clearly derived from the temperature evolution. During heating/cooling demand, borehole temperatures drop/raise before stabilizing. When heating/cooling demand stops, borehole temperatures tend to recover rather quickly. Temperature differences along the borehole length are probably related to the local soil thermal conductivity and borehole thermal resistance (Figure 57). For instance, higher thermal conductivity will lead to less temperature increase during heating demand (e.g. at 30m depth).

In addition to the temperature measurements in one of the boreholes, the energy flows at the heat pumps are also being recorded. All this data will be very useful for future research.

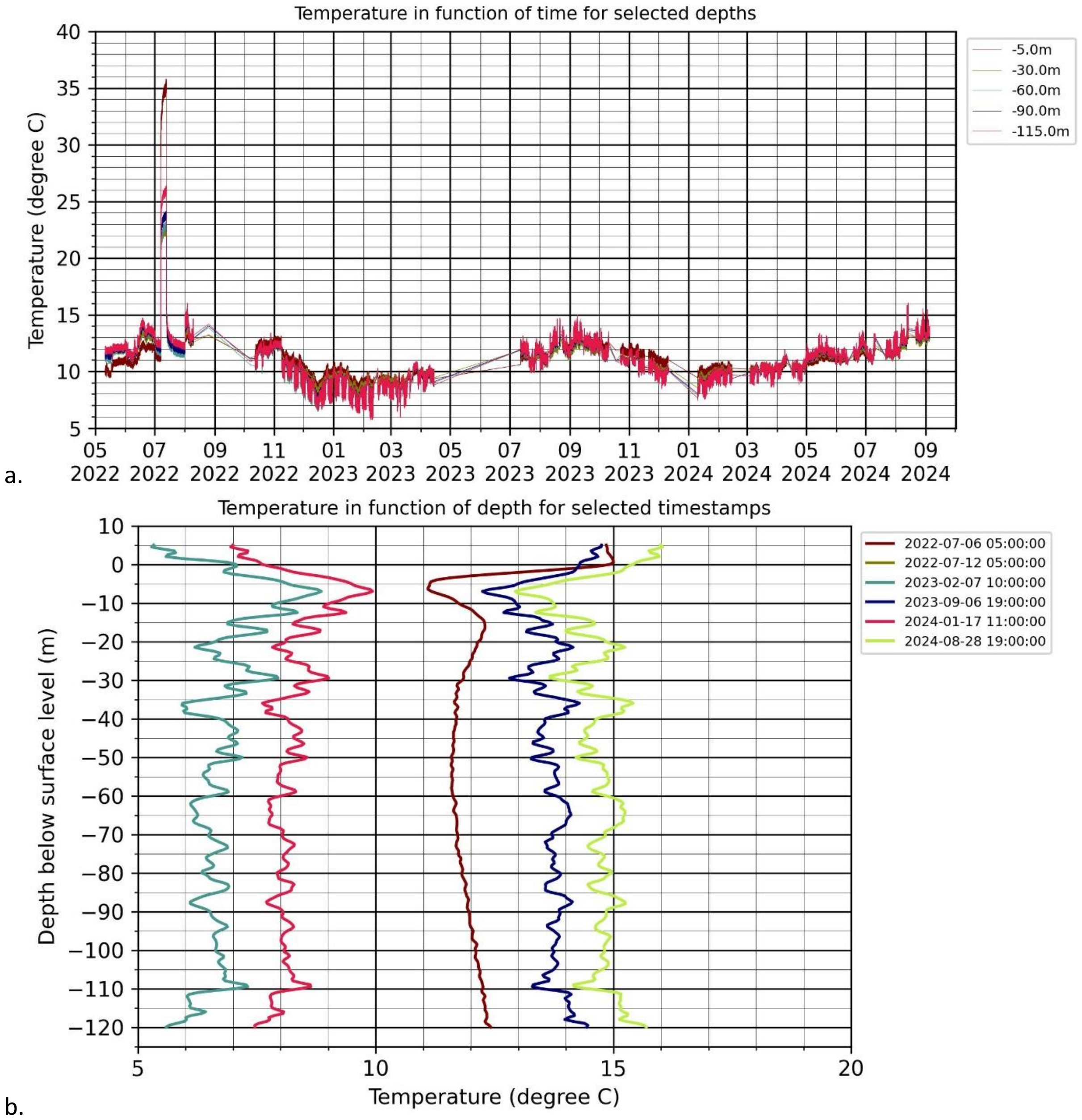
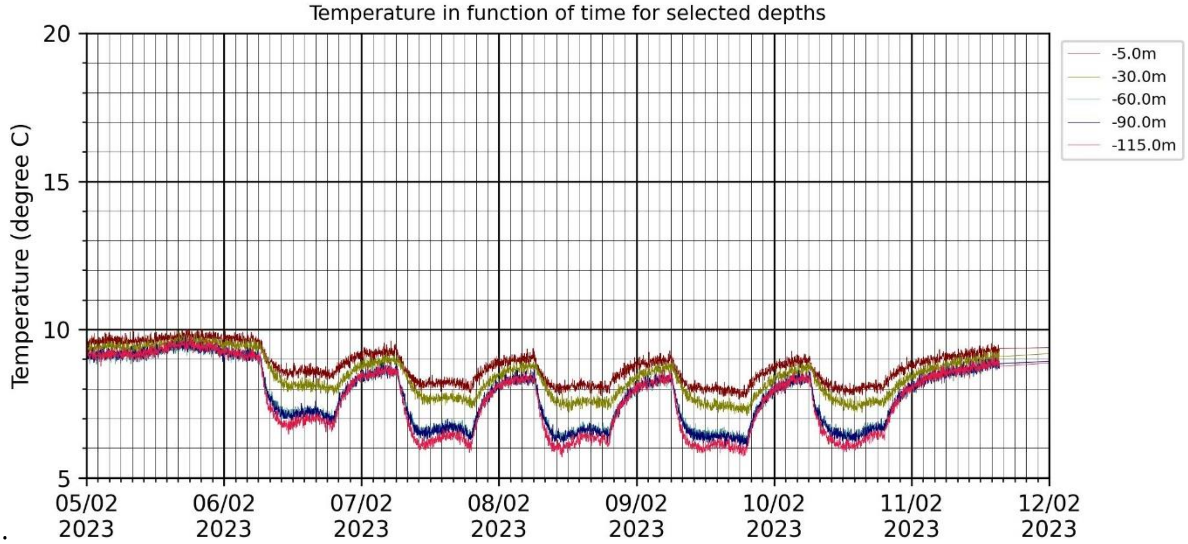
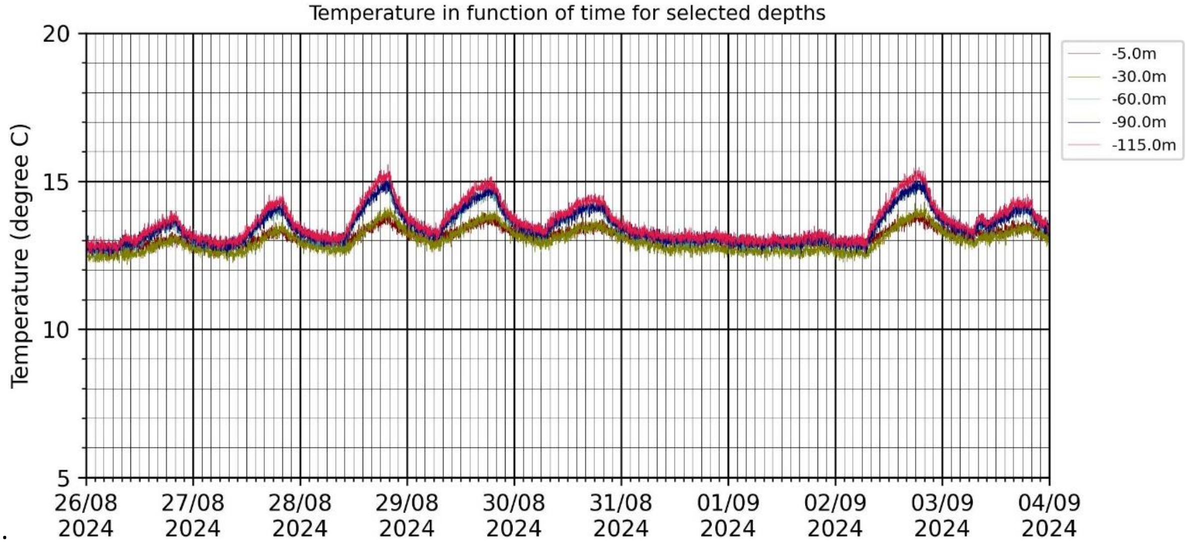


*Figure 55 (a) Temperature along the borehole depth at selected timestamps before (06/07/2022) and during operation of the BHE field. (b) Timeseries of the borehole temperatures at several borehole depths. The temperature peak in July 2022 is caused by the execution of an ETRT (results see **Error! Reference source not found.**).*



a.



b.

Figure 56. Zooms of the temperature evolution at several borehole depths. (a) During winter. (b) During summer.

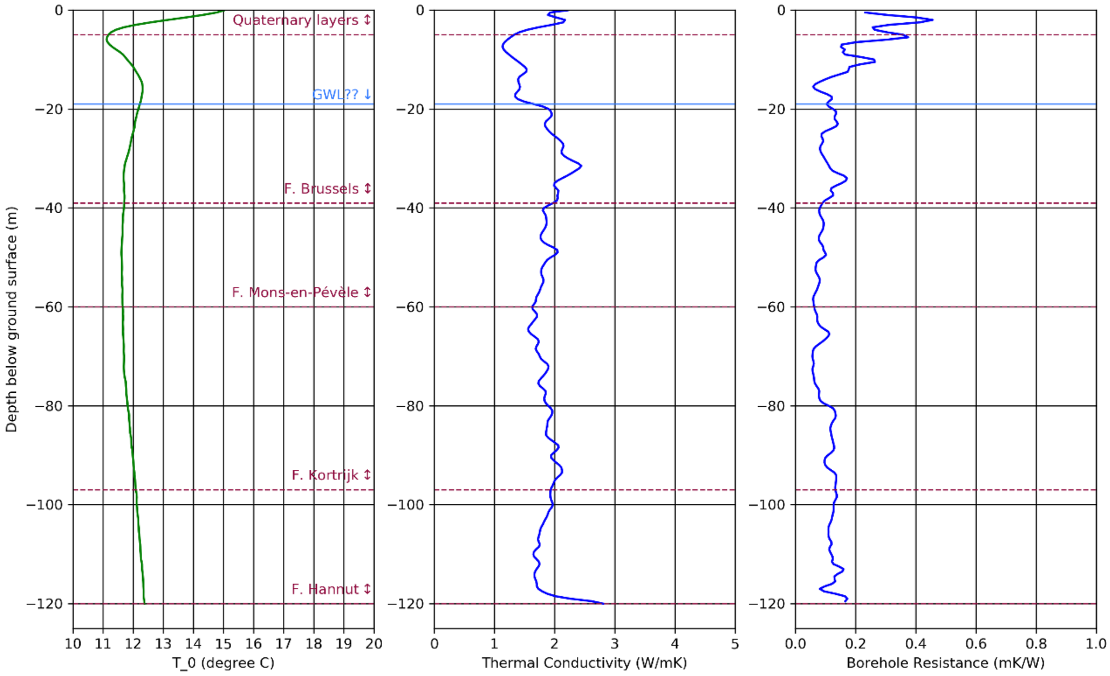


Figure 57. Results of the ETRT performed on a borehole of the Buildwise headquarters in Zaventem.

4.5. Status and next steps

4.5.1. Evolution of Brabant Massif observation points between 2020 and 2024 at Brussels

Before GeoCamb, the Brugeo project (ERDF-Brussels funding) created a geoscientific tool (Brugeotool) based on the 3D geological model of Brussels (Brustrati-3D project info here; report of Brustrati3D project). This geological model considered about 8600 boreholes in the soft cover and 668 boreholes in the Brabant Massif (Figure 58).

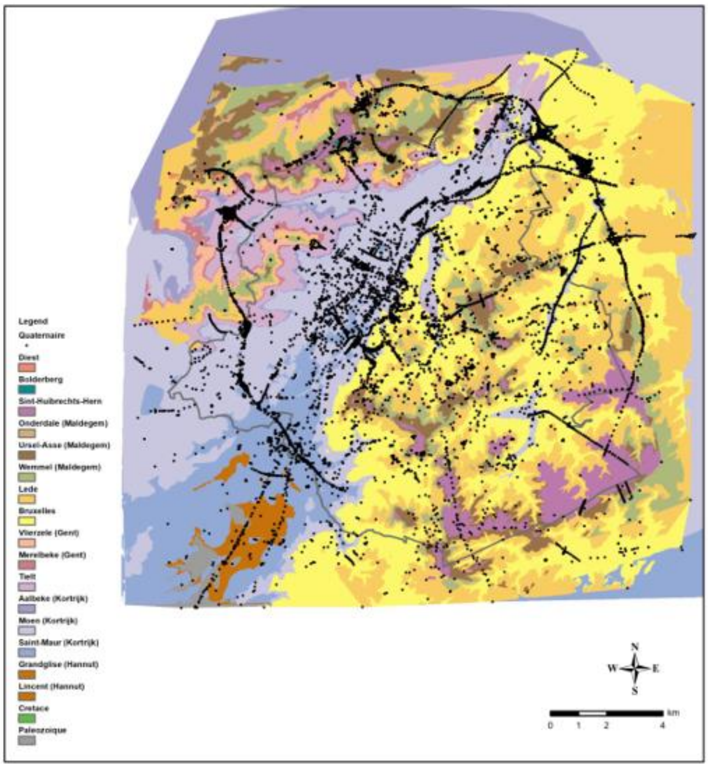


Figure 58 : Geological map of Brussels and all the information points used for the 3D modelisation (in black) in the scope of the Brustrati3D project (2018).

During the GeoCamb project, 107 boreholes were collected and studied to improve Cambrian geological knowledge (Figure 59). Only 9 boreholes were in the Blanmont Formation (BLM), and the majority belong to the Tubize Formation (TUB). Tests with magnets could confirm the presence of magnetic minerals and hence the identification of TUB (Figure 60).

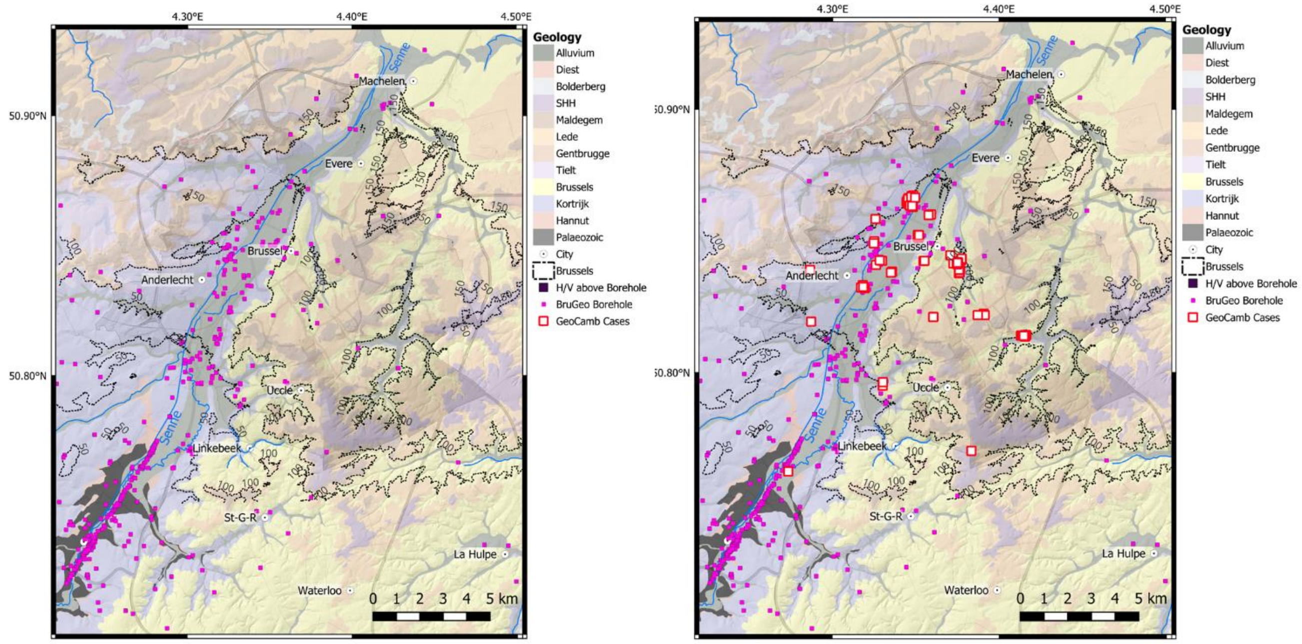


Figure 59 : Geological map of Brussels with boreholes reaching the Brabant Massif. Left: borehole situation in 2018 (Brugeo project). Right: Current situation in 2024, including the 107 boreholes (red dots) gathered in the scope of GeoCamb.

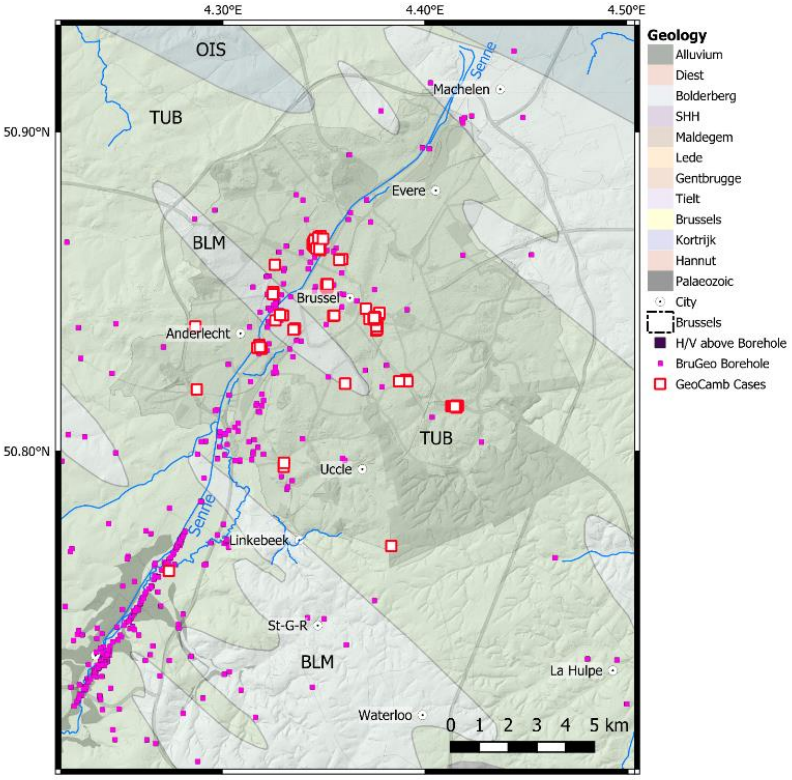


Figure 60: Geological map of the Cambrian at Brussels with GeoCamb (red dots) and BruGeo (purple) boreholes in teh Cambrian indicated. Colors in background show the presence of the Tubize Formation (TUB) and Blanmont Formation (BLM).

The project started in 2020 with 7 win-win cases and ended in 2024 with about 20 win-win cases (Figure 61**Error! Reference source not found.**). The win-win cases were private or public geothermal projects, most of them are located in the Brussels region, 2 in the Walloon Brabant, and one in Flemish Brabant. The drilling operations follow-up, cuttings samples collection and lithological interpretation were performed of each of them. Some extra tests (ETRT, pumping tests, geophysical logging, or monitoring) were realized for 9 cases.

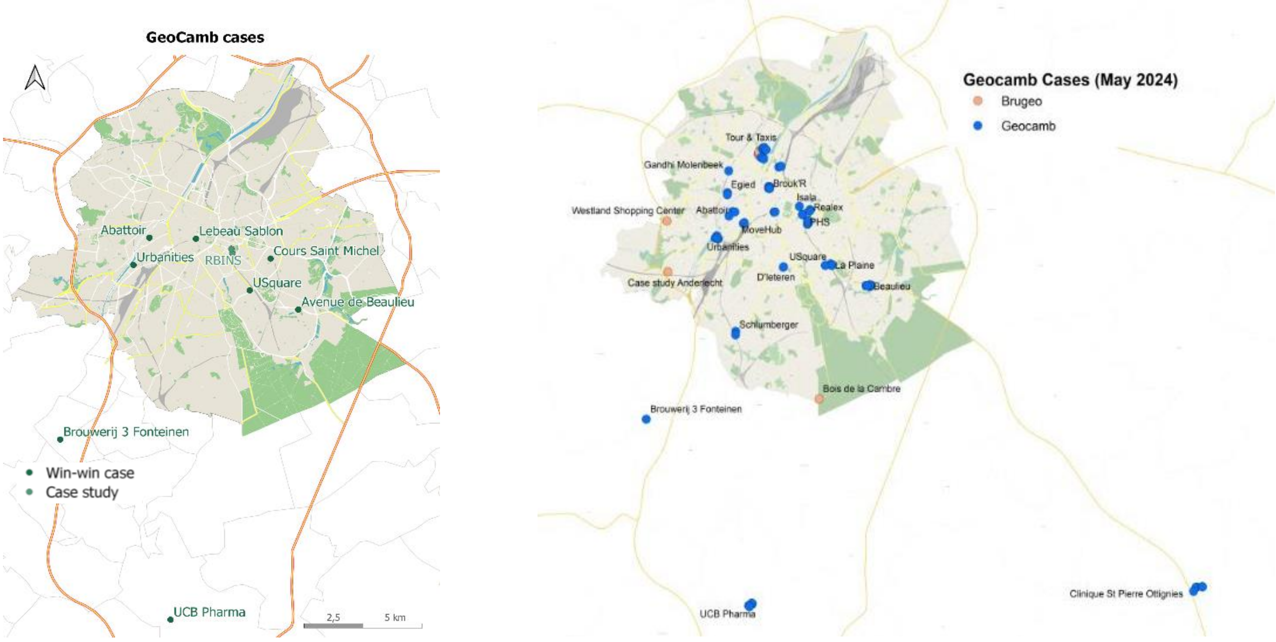


Figure 61 Geocamb and Brugeo Cases studies in 2020 (right) and 2024 (left)

The detailed results of the win-win case are not publicly available, nevertheless the main conclusions and trends are exposed in the next sections.

4.5.2. Better knowledge of the Brabant Massif

4.5.2.1. Study on boreholes samples

About 65 boreholes presented some alteration bedrock facies. In the altered part of the Cambrian basement in Brussels, the dominant lithologies include schists, quartzites, and highly weathered phyllites (even sometimes sands). These rocks exhibit degradation due to physical and chemical weathering processes, such as hydrolysis and oxidation, often associated with fluid circulation enriched in oxygen and weak acids. Weathering leads to the formation of secondary minerals, including clays (illite, argilite), iron oxides, and sometimes carbonates. The samples pictures of 3 boreholes in the figure below illustrate the different lithogies encountered in the altered part of the Cambrian basement. The probable origin of this weathering lies in paleo-meteoric episodes, linked to prolonged exposure of the basement to surface or near-surface conditions during periods of tectonic stability and erosion, potentially associated with ancient climatic cycles. These alterations impact permeability and porosity, which are critical for geothermal evaluation.

UCB Pharma

ULB USquare

PHS F2

Figure 62: Samples pictures of lithofacies of the altered part of the Cambrian basement on 3 sites

The Figure 63 illustrates the spatial distribution of the altered Cambrian bedrock thickness in Brussels, with varying thickness values categorized into five classes (from 0 to 75m):

- 0 - 1 m (green): Limited alteration is observed in these areas, suggesting minimal weathering, likely closer to unaltered bedrock.
- 1 - 5 m (yellow): Shallow alteration zones are prevalent across several locations, indicative of localized weathering processes.
- 5 - 20 m (orange): Moderate thickness of altered bedrock occurs, representing significant but not extreme weathering.
- 20 - 40 m (red): Deep weathering zones are concentrated in certain areas, implying more intense alteration, possibly influenced by faulting or prolonged exposure.
- 40 - 75 m (dark red): The thickest alteration occurs sporadically, particularly in southern and eastern parts, suggesting areas of intense chemical weathering or structural control.

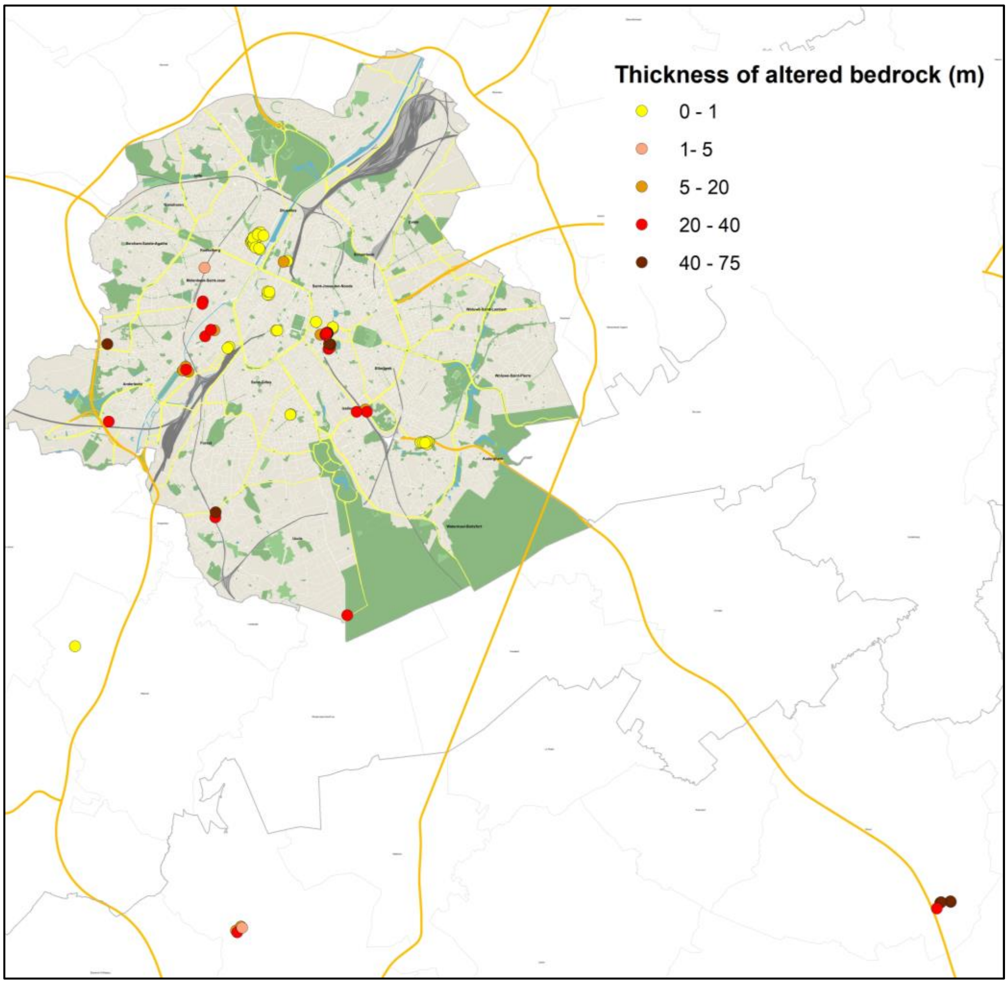


Figure 63 Thickness of altered bedrock in GeoCamb boreholes

The spatial variability in alteration thickness highlights the heterogeneous nature of the Cambrian basement, likely driven by differences in lithology, past tectonic activity, and paleo-weathering conditions. The deeper alteration zones may coincide with fault zones or areas of enhanced fluid circulation, which are important for evaluating geothermal potential. The thicker altered layer (75m) was encountered in Louvain-La Neuve case. The thickness of the altered basement seems to increase toward the south, where the basement surface is closest to the ground level.

Some extreme alteration facies with cavities were observed in PHS-F4 and Abbatoirs boreholes and 5 drillings collapsed mainly due to unconsolidated layers in the upper part of the basement. The presence of cavities about **1.5 m in length** and of unconsolidated layers in the altered Cambrian basement can raise questions about their origin, especially in a siliciclastic environment where typical karstification processes (linked to carbonates) are less expected. Siliciclastic environments such as quartzites, sandstones, and schists are not as susceptible to dissolution as carbonates (limestones, dolomites), but karst-like features can still form under specific conditions. In this case, cavities could result from prolonged chemical weathering of feldspathic components or other less stable minerals present in the siliciclastic matrix. The alteration of silicates (like feldspars) can lead to dissolution and the formation of clays and voids. Fluid circulation enriched with weak acids or hydrothermal activity can enhance selective dissolution of less stable silicate minerals. During long periods of surface exposure (paleo-meteoric conditions), physical and chemical weathering processes could have gradually altered the bedrock, leading to voids or pockets. This is especially relevant for rocks containing both quartz and feldspar, where feldspar alters to clay minerals, leaving behind residual cavities. Over time, this process can enlarge fractures or weak zones, creating significant cavities. Faults, joints, and fractures in the Cambrian basement could have served as pathways for fluid movement, focusing weathering processes along these weak zones and resulting in **solution-widened voids**.

The presence of cavities **can** be linked to **localized dissolution processes** driven by hydrothermal fluids, paleo-weathering, and structural weaknesses. These processes can mimic karst-like features, particularly where chemically unstable silicates have been altered and removed. Thus, the observed cavities could represent a form of **pseudokarstification** in the altered Cambrian bedrock of Brussels.

GeoCamb database

In total, 107 boreholes are present in the GeoCamb database: 47 boreholes (5 sites) come from Brugeo project and 60 boreholes (22 sites) were collected during the GeoCamb project. Among them 36 are closed geothermal systems, 12 are exploration wells, 52 are open systems, 2 piezometers and 5 are abandoned wells.

The database includes the following parameters: borehole info (driller, client, coordinates), drilling parameters (diameter, total depth, casing), type of borehole (open /closed geothermal system, piezometer, exploration drilling), depth to top of the weathered Cambrian (in meter), depth of un-weathered Cambrian (in meter), hydrogeological data (transmissivity and/or yield), temperature data of the well.

Borehole temperature measurements were acquired in 13 sites from 10,4 °C to 14,3°C in the city center of Brussels. Several temperature data monitoring is still ongoing and will continue after the project: Gare Maritime (10 wells) in the Cambrian, Bruxelles Environement (6 wells) in the Landenian, single house (Ixelles), USquare, Chaumont Gistoux.

4.5.2.2. Hydrogeology

As the dataset with specific well yields, transmissivities, specific well capacities showed that the spatial correlation scale of aquifer transmissivity is small. Flow loggings now also indicate that groundwater inflow in wells comes mainly from only a limited productive depth interval, typically no more than a few meters thick, likely correlated with the occurrence of fractures, and that the depth position of these production intervals can change on short distance.

The geophysical log in the deepened F3 well at the PHS site has shown little lithologic variation in the deepened part (between 200 and 300 m) but does show variations in the geophysical parameters.

A software tool developed for interpretation of pumping tests based on the analytical solution of Barker (1988), that uses the concept of fractional flow dimension, was tested with the data of a pumping test in Anderlecht. A value of 1.72 for the flow dimension was found which indicates that flow was not pure radial. Transmissivity is around 60 m²/day while the well was drilled ca 50 m into the basement rocks. Similarly, the tool has been also applied for the first phase of the step drawdown test data of the Molenbeek case study well. A flow dimension (n) value of approximately 2 was obtained, showing the characteristics of pure radial flow regime at this well. A transmissivity of 16.9 m²/day is obtained which is close to the value found by the STEPMASTER method of Eden-Hazel that uses the whole four phases of step drawdown data. The flow regime variation at the two wells shows spatial variability of the aquifer characteristics and its potential. There is high potential where the fracture dominates and low where there is less rock fracturing.

Also, among 107 case study wells, transmissivity values for about 29 wells (mostly in the Brussels region) were obtained, and the results show a high spatial variability. Similarly, the calculated Specific well capacities at 82 wells (Figure 64) portray a high spatial variability which has no spatial correlation.

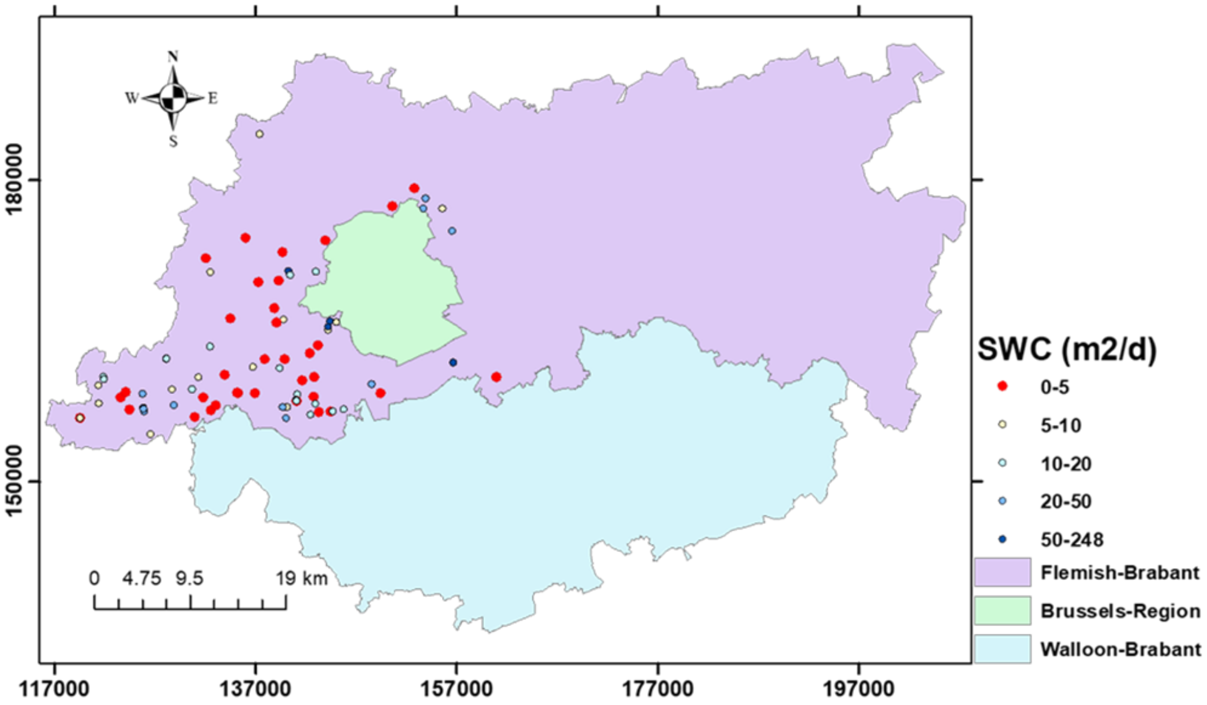


Figure 64 : Specific well capacity values calculated for 82 wells.

This variation suggests that geothermal energy resources in the region are not uniformly distributed, and that site-specific assessments are crucial for effective resource utilization.

The interpretation of time-series groundwater level data indicates a significant recovery in groundwater piezometer in recent years. This recovery marks a reversal of the long-term decline observed since the industrial period. Since 2005/2006, the implementation of strict pumping restrictions by the Flemish Government has been a key factor in this positive trend. This development is highly beneficial for the long-term potential and sustainability of the Cambrian aquifer.

4.5.2.3. Geophysics

Before GeoCamb, the ROB coordinated numerous geophysical campaigns during which mobile seismic stations were installed for various purposes. However, the raw and processed data of these campaigns were never compiled into one integrated database. The initial starting point of GeoCamb was to collect all the raw ambient noise data and processed data into one database named: the ROB HVSR database for Belgium. This initial task was finished in 2021 and reported in the ROB internship report of Scherps

(2021). Before GeoCamb, the HVSR database included ~2000 HVSR points, all over Belgium, with 683 measurements from the Brussels' capital region. During GeoCamb an additional 358 new HVSR measurements were collected above boreholes of interest and near sites that would be potentially interested in installing a bedrock geothermal system in the future. The initial list was based on BruGeo sites of interest and ATES and BTES sites around Brussels. All new measurements were automatically included in the HVSR database to follow the consistent structure. The GeoCamb HVSR database comprises a total of 358 individual ambient noise measurements at 66 places in and around Brussels. Figure 65 below shows the HVSR points before (yellow dots) and after (red dots) the GeoCamb project. Figure 66 show the results after HVSR analysis and show variation of resonance frequency (f0) in Brussels. F0 varies from 9 Hz in the south (region of Halle) to 0.64 Hz in the north, demonstrating the increase in sediment thickness because of the dipping Brabant Massif to the north.

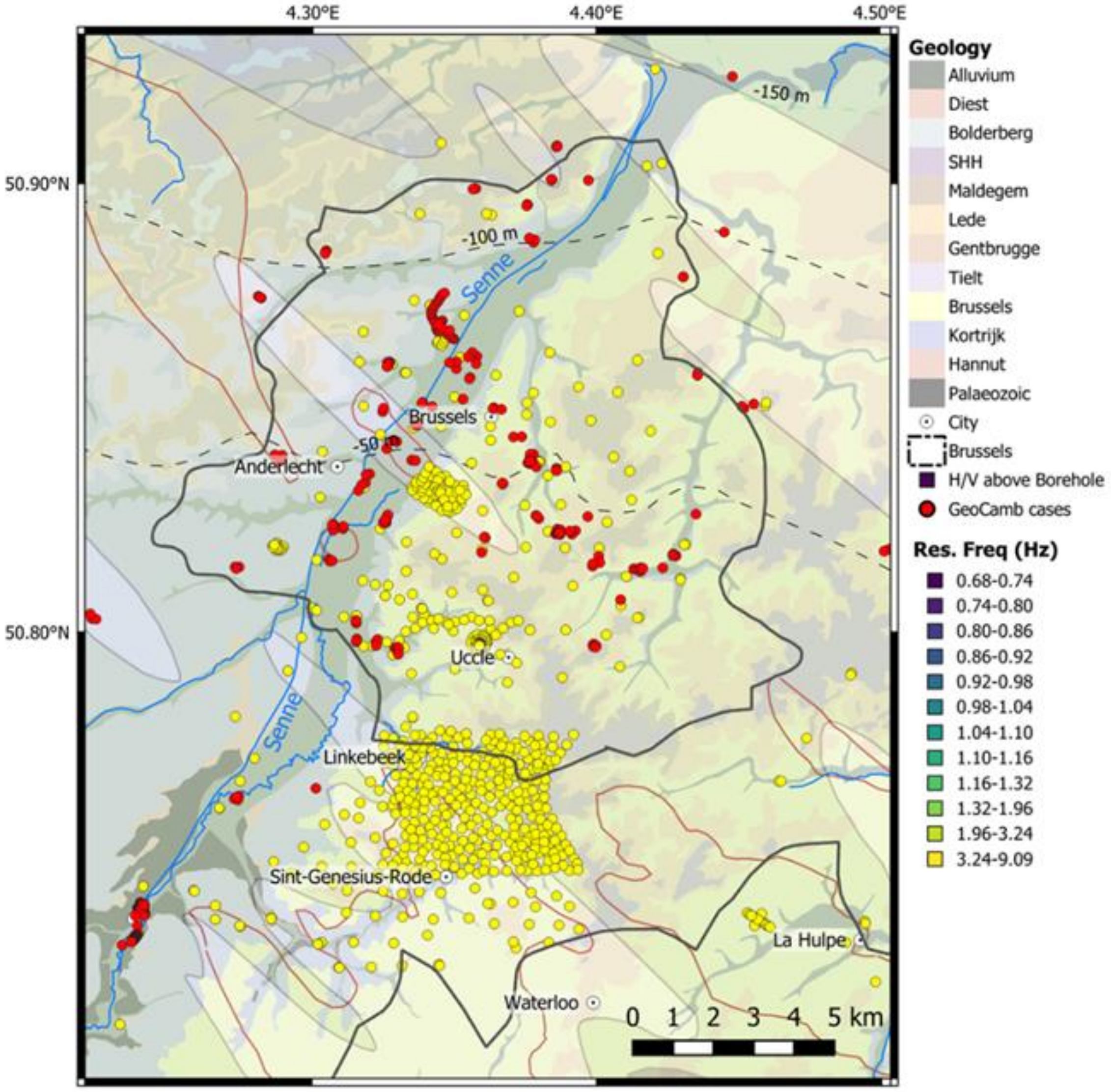


Figure 65: HVSR points before (yellow) and with the GeoCamb (red) project

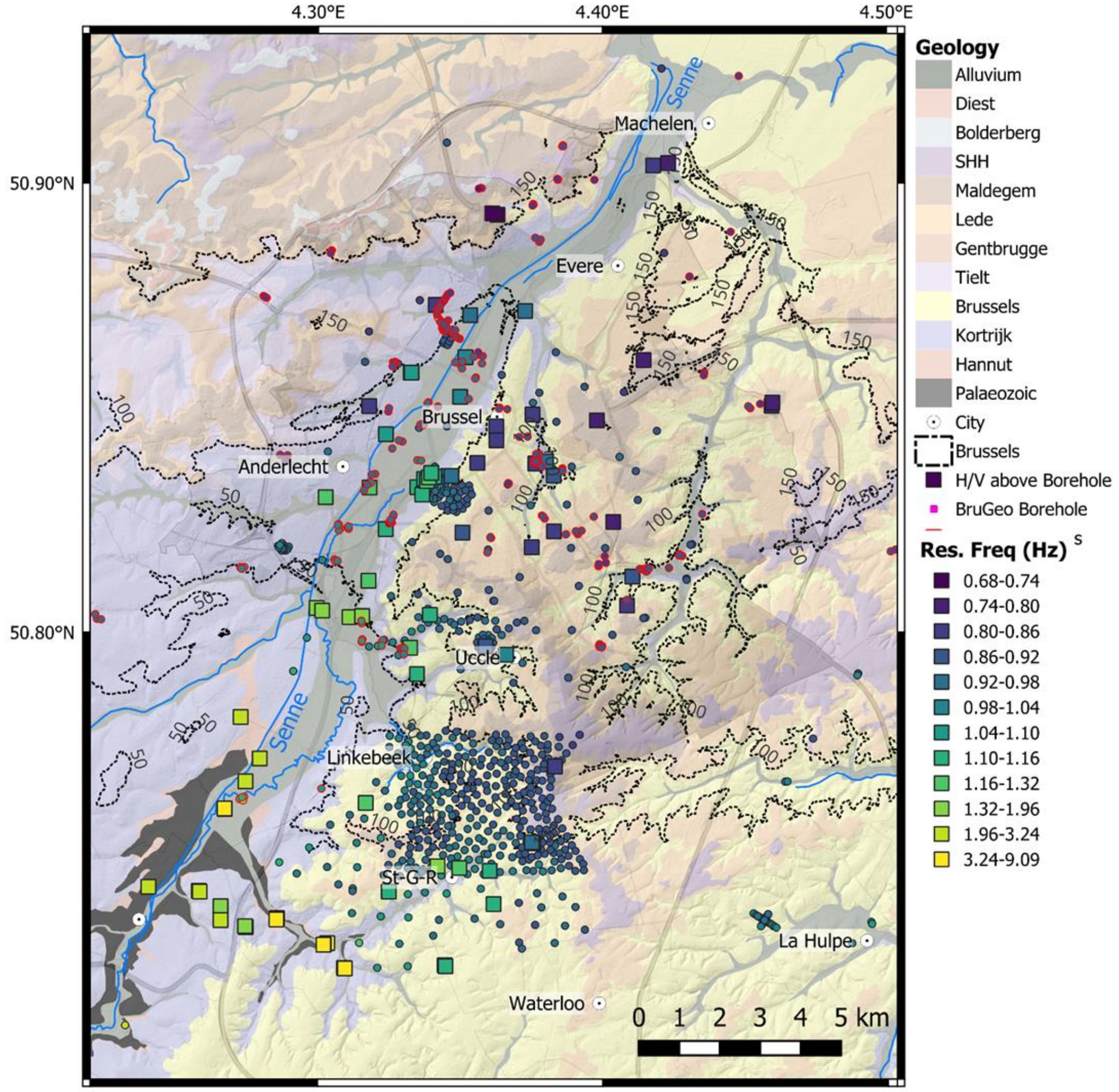


Figure 66 : Overview of the HVSR database around Brussels, illustrated on top of the geological map of Brussels. Coloured dots indicate resonance frequency of measurements where bedrock is not known. Squared symbols indicate measurements above boreholes. Dotted lines show contours of depth to the Brabant Massif.

In a next step, we converted all HVSR measurements to depth and also included those boreholes of BruGeo that reach the Brabant Massif. Especially new drillings, such as those of the Ghandilaan case-study and PHS, confirmed the power of the HVSR technique and the similarity of results between the current 3D model and the geophysical measurements. In one case, we were even able to correct the borehole log based on geophysical measurements. In the P2 borehole in Abattoir, bedrock of the Brabant Massif is described already a depth of 47 m. However, HVSR results show an f0 of 1.075 Hz, which converted to depth using the Van Noten et al. (2022) conversion law gives 78 m depth (see left side of Figure 67 below). Hence, this borehole log (middle) should be revised.

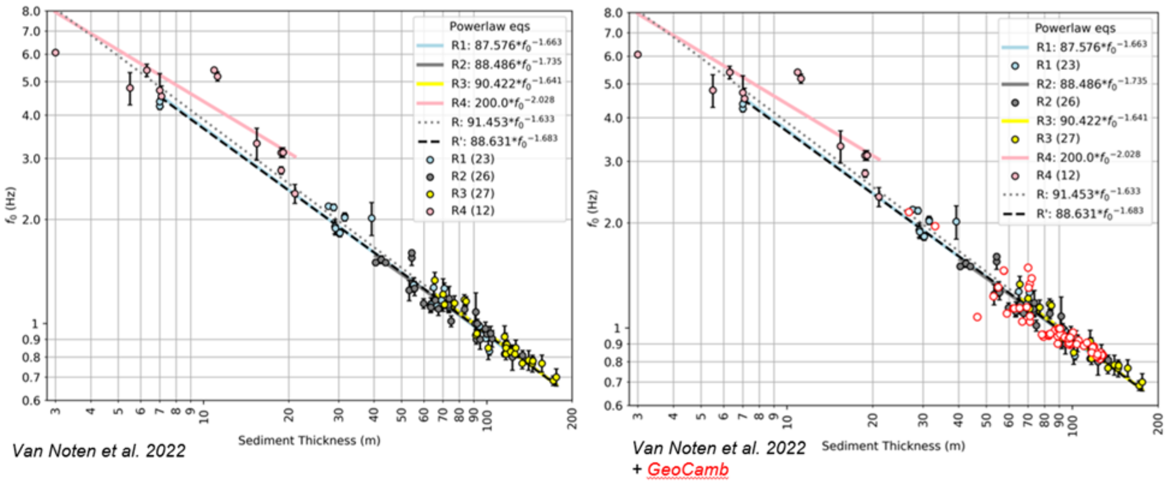


Figure 67 : HVSR measurement and virtual borehole above P2 of the Abatoir site. HVSR shows that the borehole log should be corrected and that bedrock depth is deeper than what is explained in the log (78 m versus 47 m).

The linear profile that was conducted in the parc next to the Tour & Taxis site (see next chapter), also shows that in places where no boreholes were used in the interpolation of the 3D model, HVSR can definitely help to improve the 3D model. Currently, 1202 points can already be used to better model the palaeotopography of the Brabant Massif and to update the bedrock model in the online BruGeoTool.

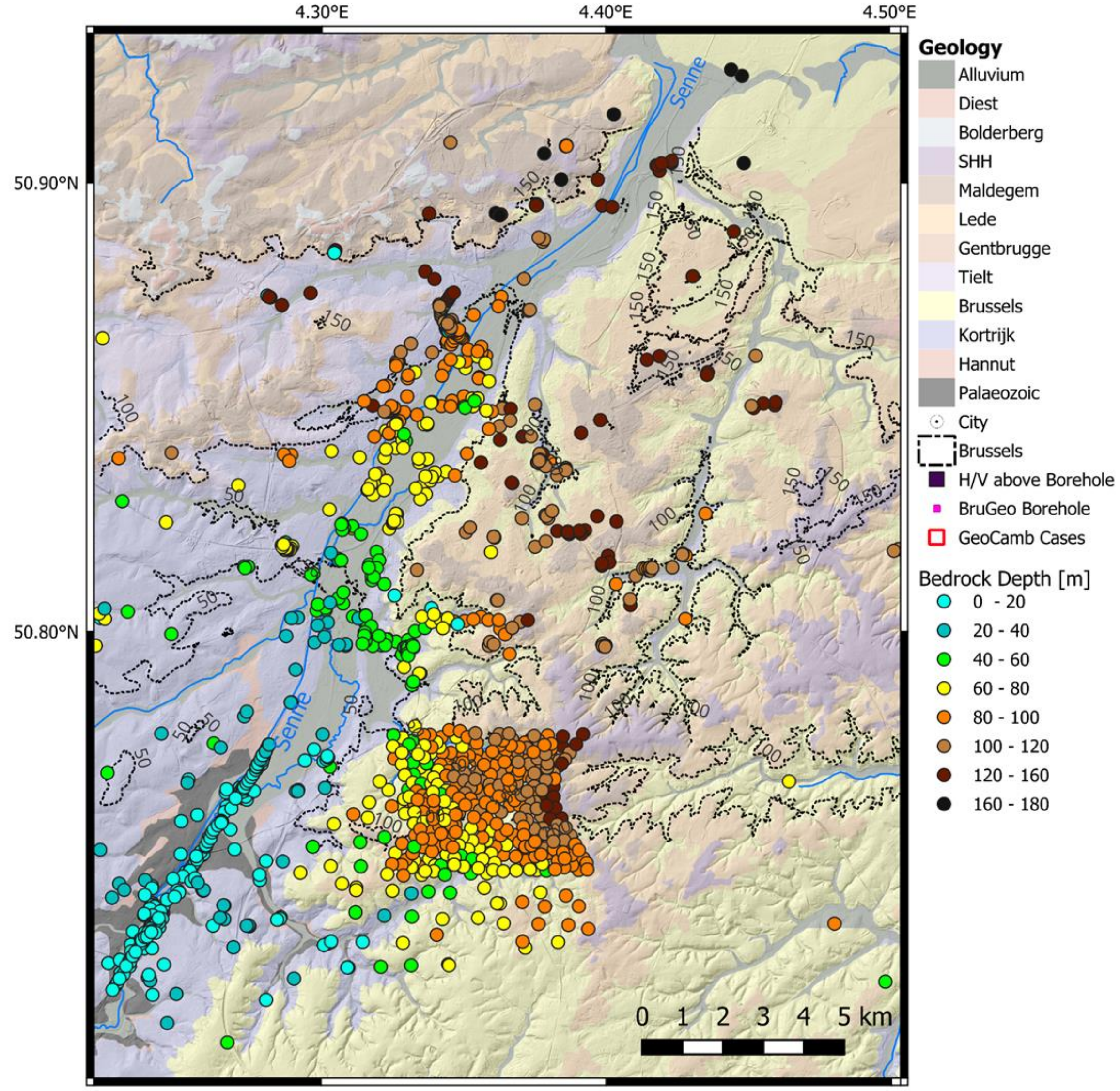


Figure 68 : Bedrock depth map. Mix between BruGeo and Geocamb boreholes and HVSR measurements converted to depth around Brussels. 1202 points can currently be used to improve bedrock depth modelling and better study the variability of the palaeotopography of the Brabant Massif.

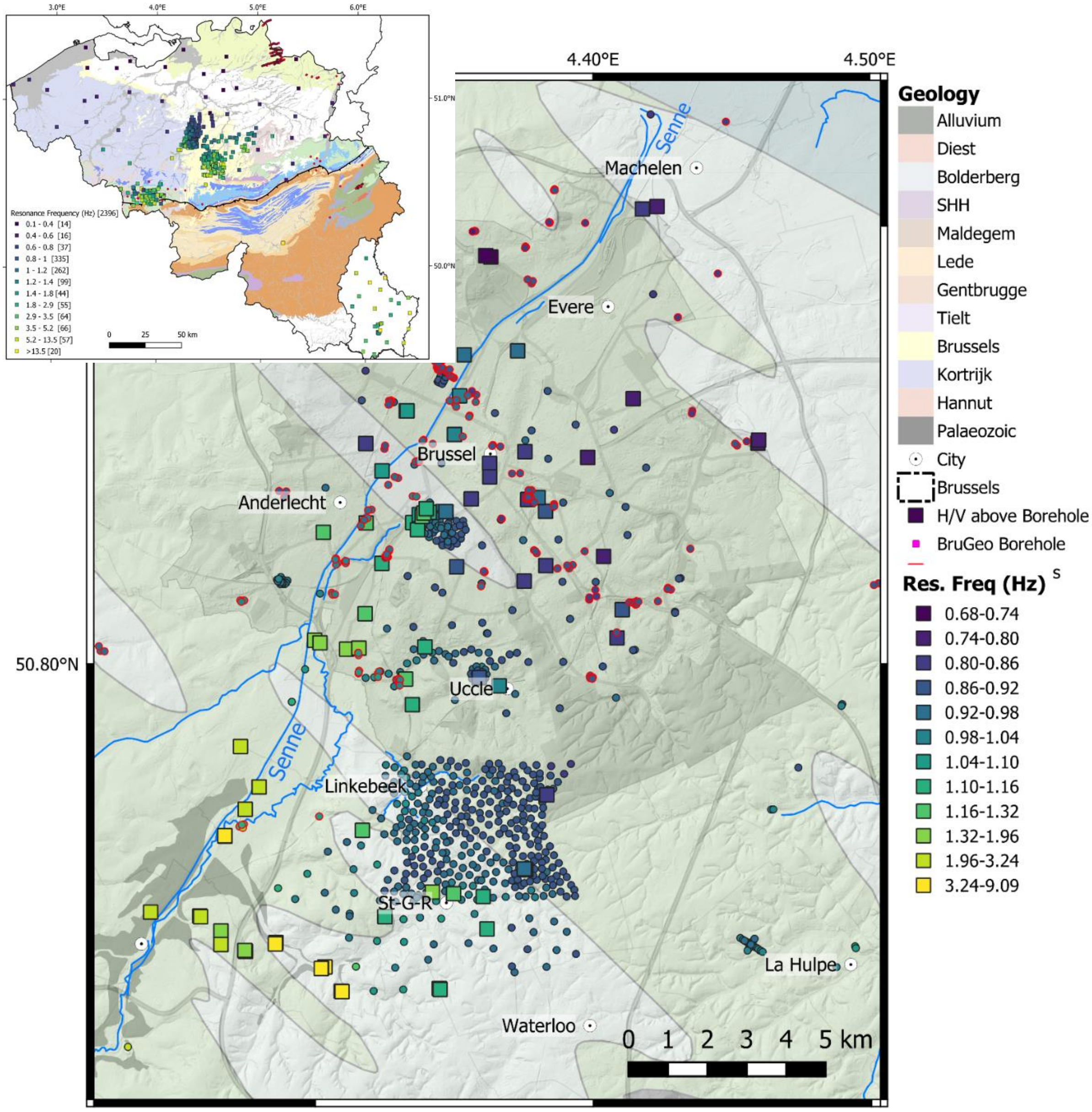


Figure 69 : Top right: HVSR database for Belgium. Map: Resonance frequency map around Brussels with bedrock typology in the background (Tubize Formation: dark green, Blanmont Formation: light green).

We also better quantified the relation between resonance frequency and bedrock depth and can conclude that we accurately can use the HVSR method to predict bedrock in Brussels. This is clearly shown if we plot all the GeoCamb measurements on top of the original powerlaw relation. This result is a major achievement for the GeoCamb project and for future geothermal projects in and near Brussels. A scientific paper is being prepared to publish the Belgian HVSR database (currently 4408 measurements), of course including the GeoCamb measurements.

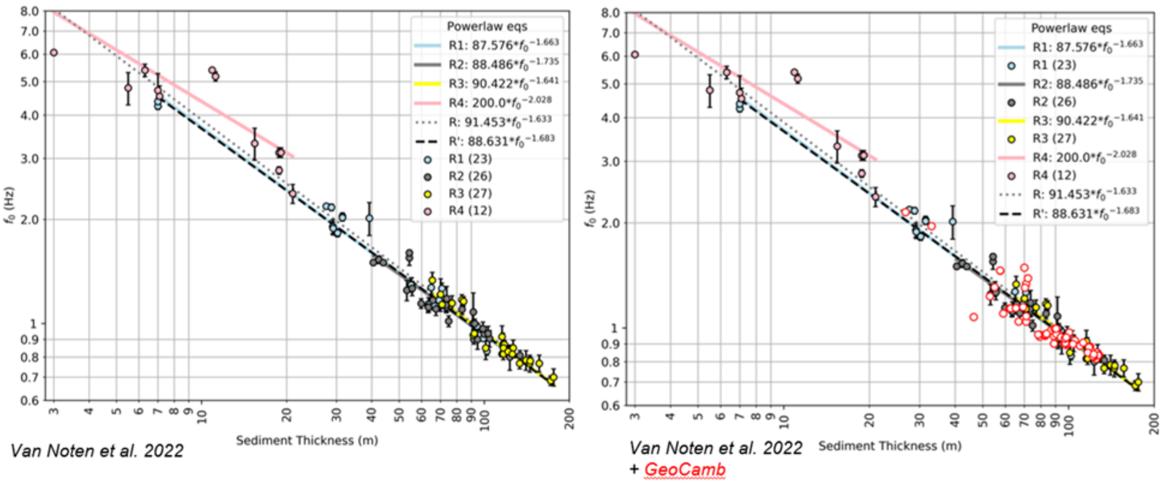


Figure 70 : Left: Original powerlaw relation between resonance frequency and depth (Van Noten et al. 2022). Right: GeoCamb HVSR measurements added to the graph, confirming the power of using this powerlaw to predict bedrock depth in Brussels.

Another important result of the GeoCamb project was obtained by comparing the resonance frequency values with either the depth to the top of the bedrock (i.e. the weathered part) or the depth to the unweathered/fresh part of the bedrock. For years, a discussion was ongoing if HVSR "sees" the weathered (altered) or unweathered top of the bedrock. The figure in below shows a comparison of the f0 with the top of the bedrock (coloured points) and top of the fresh part of the bedrock (blue dots). It is very clear that the blue dots do not follow a classic powerlaw relation which is generally agreed in literature as relation between f0 and depth. Hence, we finally can conclude that HVSR can be used for bedrock depth modelling and modelling the soft sediment thickness below Brussels. However, the technique cannot see the thickness of the weathered part of the bedrock.

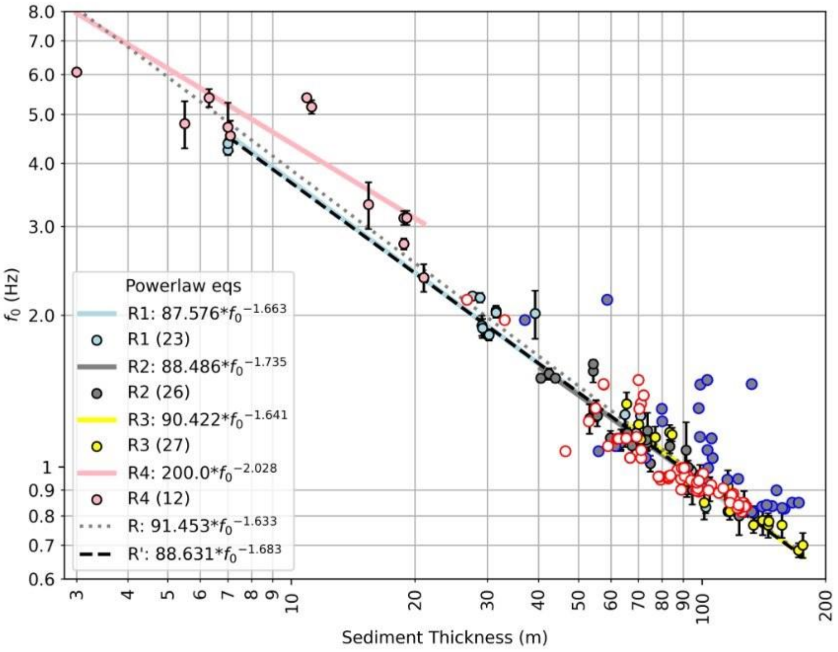


Figure 71 : Final proof that HVSR analysis detects the top of the bedrock, i.e. Brabant Massif below Brussels (red dots) and not the top of the un-weathered part of the bedrock (blue dots).

4.5.3. Succes rate of geothermal systems

Figure 72: Evolution of the amount of SGE systems at Brussels between 2021 (left) and 2024 (right).

Evolution of the amount of SGE systems between 2021 and 2024.

A clear trend toward Closed Systems (Figure 73): Between 2021 and 2024, there has been a significant increase in the number of closed-loop geothermal systems (BTES) (red dots). This indicates a growing preference for systems that are more self-contained, likely due to their versatility and lower environmental impact compared to open systems. While the open-loop systems (ATES) (blue dots) have also expanded, their growth appears more limited compared to closed systems. This could reflect technical or regulatory challenges. Nevertheless, these maps indicate only geothermal systems permitted, a certain amount of exploration drilling for open systems have been conducted the last 2 years. The spread of geothermal systems has become more balanced across the city. Closed systems, in particular, now cover areas where they were previously sparse, such as Schaerbeek and the northern parts of Brussels. Open systems, meanwhile, remain more concentrated in specific areas, particularly in the Senne valley axis and near large buildings or institutions that can accommodate such setups. The dominance of closed systems could also be tied to their suitability for urban environments, where space is limited, and groundwater regulations restrict the implementation of open systems. The clustering of blue dots near the European Quarter and other institutional zones suggests that open systems are still predominantly used for larger-scale projects, such as government or public buildings, or where the thermal energy demand is higher.
The faster adoption of closed systems may reflect advancements in drilling and accessibility of this technology, coupled with supportive policies for energy efficiency in private and residential sectors. Open systems, while still growing, face more technical challenges that limit their rate of adoption.

The 2024 map shows numerous ongoing projects for open systems. However, if the current trend persists, closed systems may continue to dominate due to their adaptability and ease of integration in diverse urban settings.

On the 69 wells drilled for open systems in the Cambrian basement: 5 collapsed or are inaccessible (7,2%), 9 gave flow rate <20m^3/h (13%). **This gives a rate of success of about 79.72%,** which seems to be very encouraging in view of the variability observed in the hydraulic parameters of the Cambrian basement.

4.5.4. Performance of geothermal systems

The case studies of work package 4 illustrate very clearly the functioning of closed and open loop geothermal systems (see chapter 4.4 and the dedicated Buildwise reports). The work showed that in geothermal systems, it is crucial to provide adequate monitoring, especially during the system's startup, and to ensure proper follow-up. Over the longer term, it is also important to ensure that the thermal balance is maintained, or at least remains as it was intended in the geothermal system's design. Moreover, small adjustments to the controls can have a significant impact on the efficiency and long-term operation of such systems. Furthermore, it was shown how available software packages for the design of closed-loop geothermal systems can be used to perform a back analysis of the monitoring data, allowing for adjustments to optimize long-term operation.

4.6. Potential for public buildings

As open or closed geothermal energy storage systems exchange heat with a building or a group of buildings, it is important to assess the demand profile of these buildings. Heat source and sink should be matched, and a balance in time should be attained to achieve a stable system. To study the potential for geothermal energy in public building (sites) 5 cases have been studied:

- An apartment building from 1970 to be renovated at Molenbeek
- A dwelling and possible heat network grid from the Logement Anderlechtois
- A museum wing and office building of the RBINS site next to the PHS building

The first site at Molenbeek is already covered in chapter 4.2, with a large range of tests and feasibility studies for the geothermal source in relation to the apartment building. For the second site we only studied the building heat demands from the dwellings, but as the RBINS site is situated right next to the exploration site of the PHS building, we will focus on these cases in the next chapters.

4.6.1. Geothermal potential at PHS building

A geothermal feasibility study of the Paul-Henri Spaak building (PHS), the Brussels seat of the European Parliament, was conducted by Artesia in 2021. A brainstorming on energy mutualization between Parc Leopold neighbors started several years ago, as RBINS and PHS buildings are both conducting large renovation feasibility studies (Figure 73), it was an interesting opportunity to include the expertise of GeoCamb partners in that investigation.

Figure 73: Aerial view of PHS and RBINS buildings

The study of the geothermal potential of the Cambrian comprises three phases:

- **Exploratory Drilling (Phase 1):** Four boreholes (F1, F2, F3 and F4, see Figure 74) were drilled to investigate the subsurface, targeting the Paleozoic Basement. This phase aimed to assess its aquifer properties and thermal conductivity potential for closed-loop and open-loop geothermal systems. GeoCamb partners provided assistance in the drilling activities, detailed description of cuttings, an Enhanced TRT in the F4 drilling, two geophysical logging (F4 and F3), HVSR survey and related analysis.
- **Continuous geophysical monitoring of bedrock depth**: Parallel with the drilling operations, 21cseismic nodes were placed for 2 weeks around PHS in 2021. For most boreholes discussed in GeoCamb, nodal measurement time was only a few hours. Here, because of the availability of the private property, we took the opportunity to investigate if longer measurements/time series would improve our interpretation of the bedrock depth prediction.
- **Hydrogeological Testing (Phase 2):** Pumping and injection tests, as well as tracer experiments, were performed to determine the hydraulic conductivity of the aquifers, evaluate water movement, and measure interactions between boreholes. These activities helped validate the feasibility of using the subsurface water system for geothermal applications. The GeoCamb contribution was based on re-interpretation of some pumping tests.
- **3D Hydrogeological Modeling and System Design (Phase 3):** A detailed 3D model was created to simulate the subsurface environment, enabling a pre-dimensioning of two geothermal systems:
    - An open-loop system utilizing Aquifer Thermal Energy Storage (ATES) through pumping and reinjection wells.
    - A closed-loop system with Borehole Thermal Energy Storage (BTES) using vertical heat exchangers.

- **Continuous geophysical monitoring of bedrock depth**: Parallel with the drilling operations, 21cseismic nodes were placed for 2 weeks around PHS in 2021. For most boreholes discussed in GeoCamb, nodal measurement time was only a few hours. Here, because of the availability of the private property, we took the opportunity to investigate if longer measurements/time series would improve our interpretation of the bedrock depth prediction.

The results of phase 1

The main conclusions from the drillings, the ETRT and geophysical logging results are:

- The F2 reached a depth of 300m, the deepest borehole of Brussels.
- The thickness of unconsolidated deposits (sands and clays from the Brussels, Kortrijk, and Hannut formations) ranges from 102.5 m (F2) to 110 m (F3 and F4).
- A chalk layer measuring 9 to 11 m in thickness lies above the Paleozoic Basement.
- The top of the weathered Basement is located at depths between 112.5 m (F2) and 121 m (F3).
- The top of the intact Basement is found at depths between 141 m (F1) and 171 m (F2).
- The quality of the Basement varies between the different boreholes. Borehole F1 contained a significant fraction of clay and sand (strong weathering of the top basement), causing it to collapse.
- The weathered basement exhibits highly variable facies across boreholes: sandy layers, nearly pure quartz veins, clay layers, and fragments of sandstone and quartz ranging from millimeter to multi-centimeter sizes. Some cavities of 1,5m of length were observed in F4 between depths of 137,5m and 139m and between 141,5m and 142,7m (see Figure 75 **Error! Reference source not found.**).
- The ETRT results of F4 correspond well with the other observations (see Figure 76). The different geological layers and the boundary between weathered and fresh bedrock can be clearly distinguished in terms of thermal conductivity.

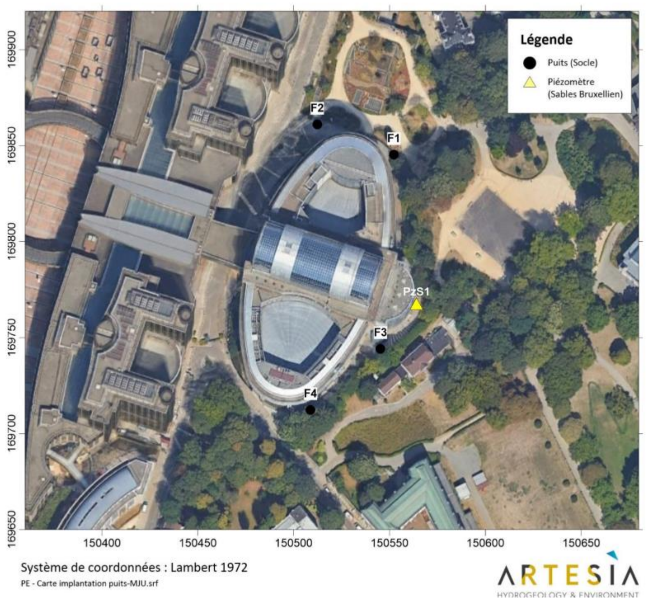


Figure 74: Location of the four PHS drillings

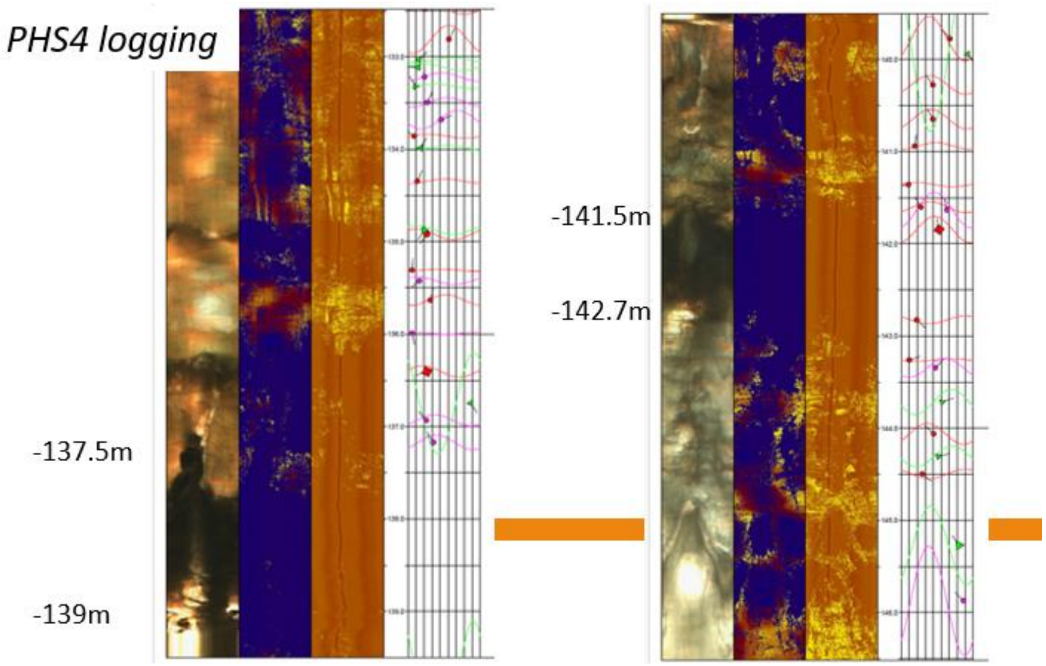


Figure 75:: Geophysical logging F4 (optical imagery, and fractures analysis)

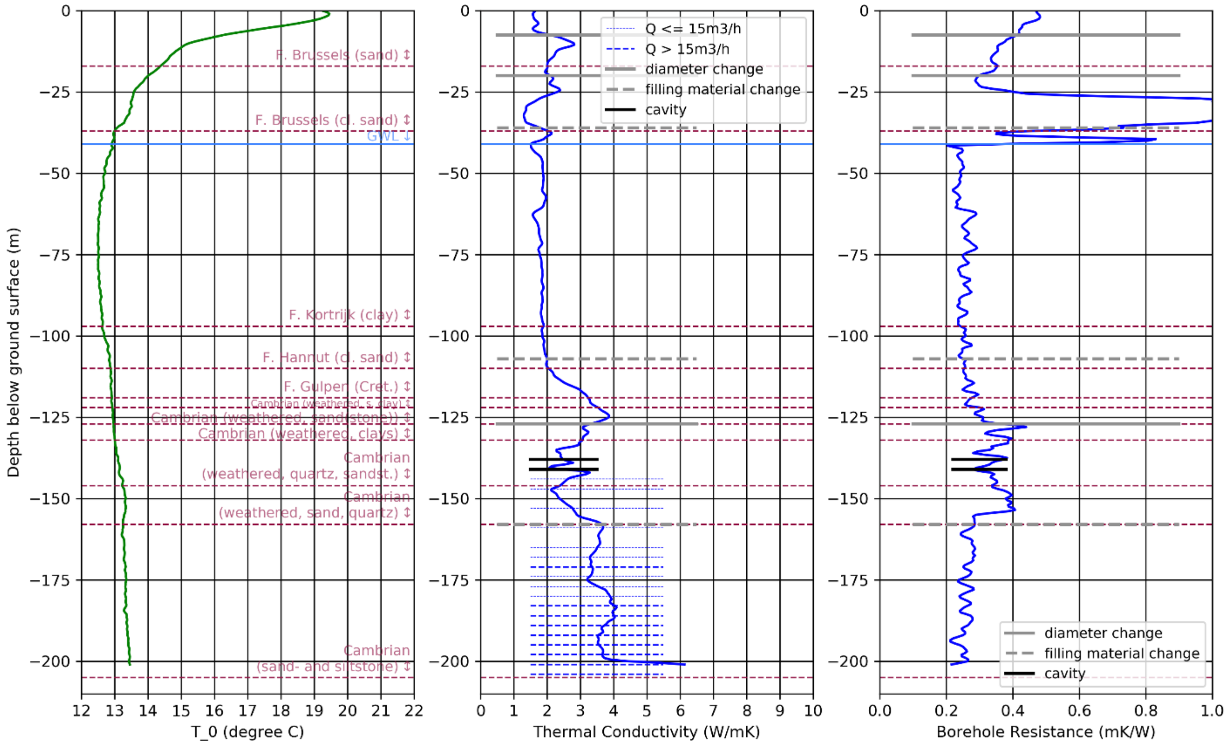


Figure 76: Results of the Enhanced Thermal Response Test (ETRT) performed at F4 of the PHS building.

Phase 2 and Phase 3 results are not publicly available.

Results of the 2-week seismic monitoring

Along the 4 drilling sites of the Paul-Henri Spaak building (PHS), 21 seismic node sensors have been installed for a duration of 17 days in July 2021 to retrieve ambient noise recordings. 16 sensors have been placed along the building in the vicinity of the drilling sites. The remaining nodes were placed in the adjacent Leopold Park to increase the overall array aperture and discern lateral variations in the subsurface structure. The side-by-side installation of seismic sensors at drilling sites is of high interest as the in-situ logging results of the drilling serve as a calibration for the non-invasive geophysical investigations performed near other potential sites of interest for GeoCamb.

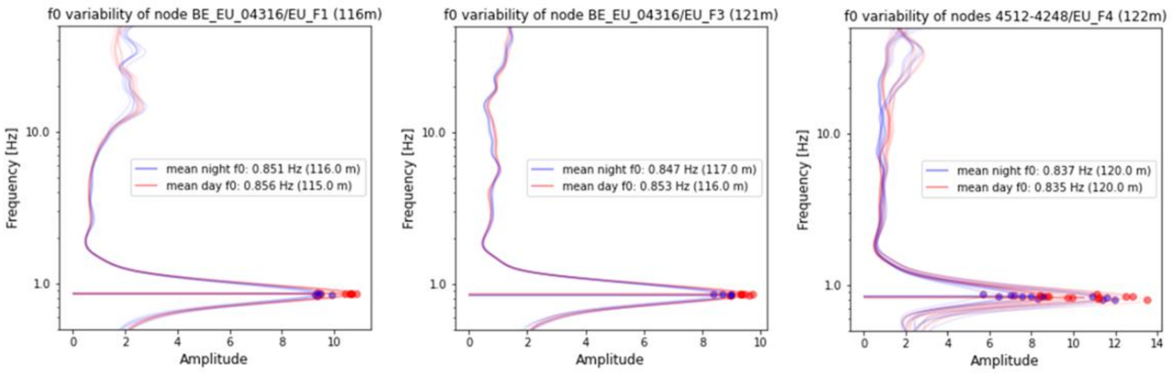


Figure 77 **:** *HVSR amplitude-frequency curves obtained from ambient noise recordings close to the PHS drillings (F1 tot F4). The resonance frequency (f0)-to-depth conversion of Van Noten et al (2022) works well in Brussels as bedrock depth predictions are close to reality, with only few meters error. Analysis of nightly recordings (blue curves/points) results in slightly better prediction than using records during the day (red curves/points)*

Continuous monitoring of ambient noise turned out to be promising and very interesting! The result below (Figure 78**Error! Reference source not found.**) shows the HVSR result of two weeks monitoring above borehole PHS F1, of which the bedrock depth was found at 116m depth (see Figure 77). The HVSR time graph shows that the Brabant Massif again is a clear reflector, which can be tracked using HVSR analysis. On the right side, the average HVSR curve is computed for two weeks, with a mean f0 value of 0.862 Hz. Converted to depth, this results in a predicted depth of 117 m as shown in the Virtual Borehole (Figure 79**Error! Reference source not found.**), which compares well with the 116 m from the drilling. The analysis shows that longer monitoring results in a more stable HVSR curve and can more accurately predict bedrock depth, than if only few hours would be measured.

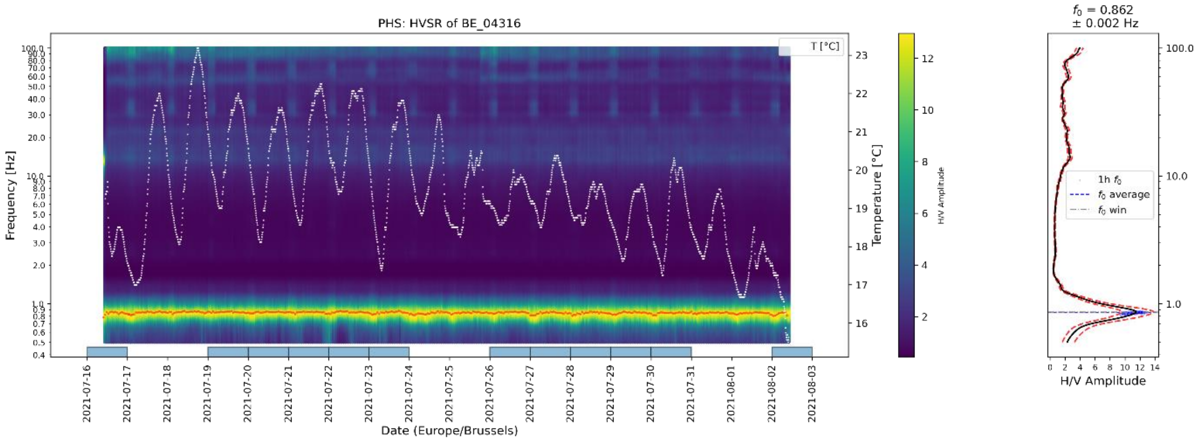


Figure 78: Two-week continuous HVSR analysis of a seismic node installed close to PHS borehole F1 in Brussels. The mean HVSR curve is computed on the right side of the graph, with a mean f0 of 0.862 Hz.

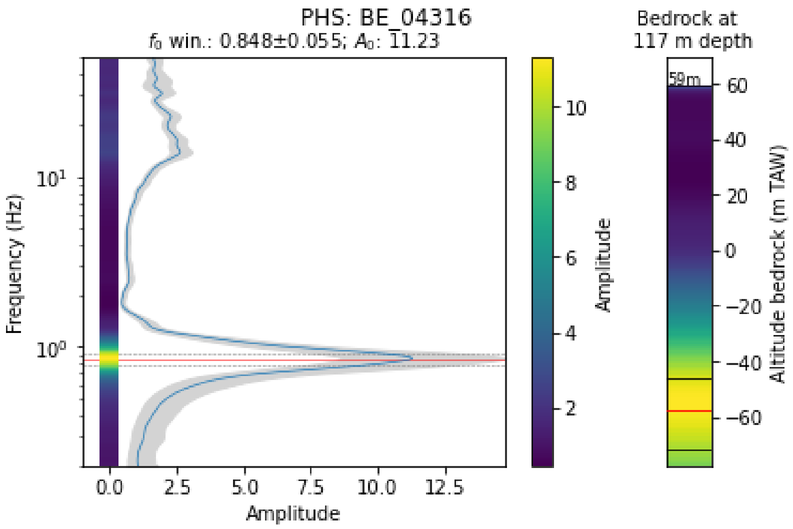


Figure 79: Virtual borehole computed from node data installed above PHS drilling F1. The predicted depth of 117 m compares well with the 116 m from the drilling.

If we zoom in on the f0 value (Figure 79), however, the value of f0 changes (see zoom Figure 80) and is less stable at night than during the day. It is known that HVSR changes through time due to the change of shear wave velocity Vs of the upper soil layers (related to temperature changes, soil moisture variability or rainfall) and changing noise sources through time. Whereas temperature and rainfall only influence the contrasts in the upper layers (see light blue color changes in the higher frequencies) , the noise content seems to affect f0 more significantly. f0 drops below 0.8 Hz in the few hours around midnight where the site is the less “noisy” and public transport and traffic stops around PHS. Hence, if only a night measurement would be taken around these hours, we thus would predict the bedrock depth differently. Based on these results, the ROB will further dive into continue HVSR monitoring for various purposes and include these average values in the ROB HVSR database.

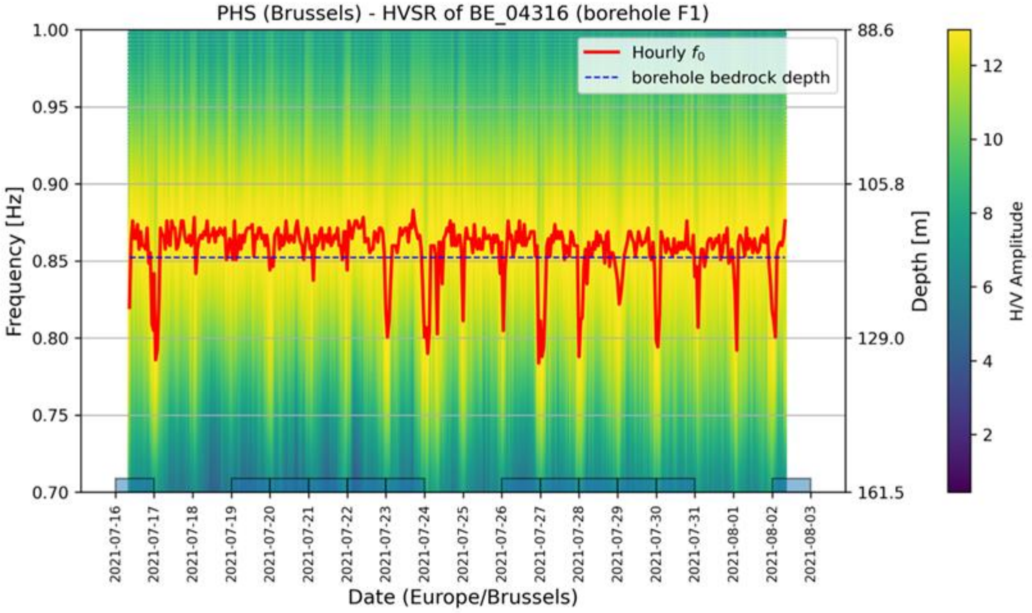


Figure 80: Variability of f0 through time. Note the f0 drop around night times, presumable related to differences in noise content.

4.6.2. Energetic study of RBINS

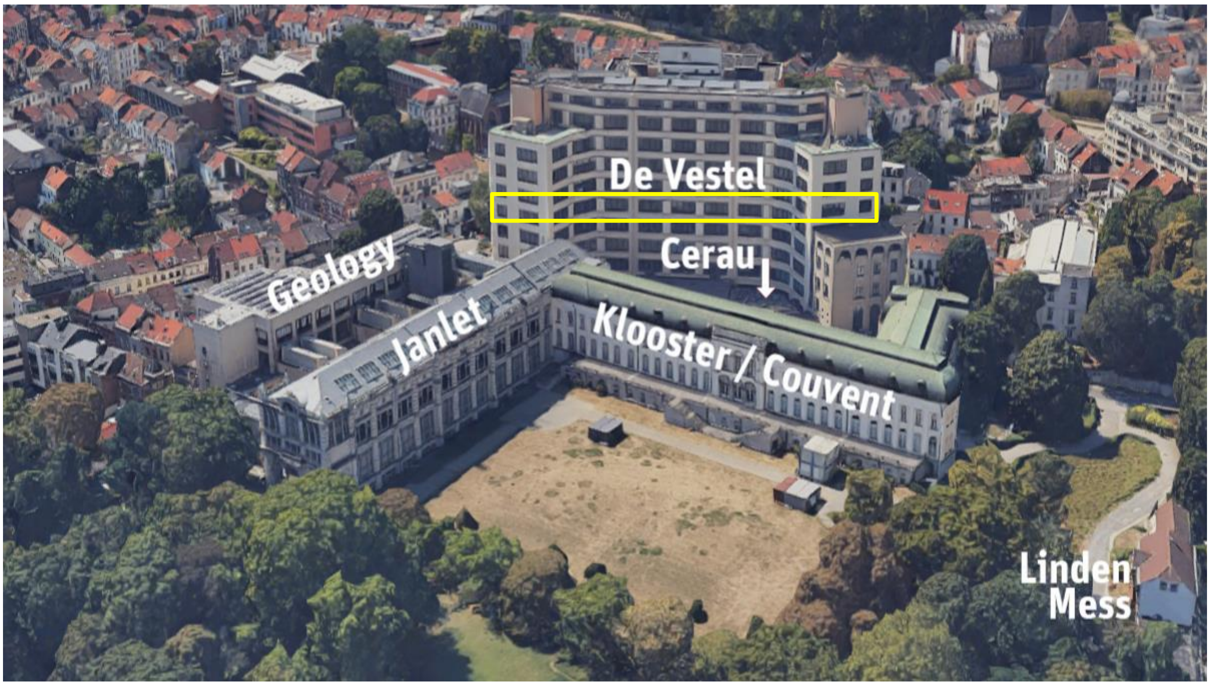


Figure 81: The RBINS building site, with the studied floor of the Vestel office building marked in yellow. (The PHS site is just on the right hand side of this picture.)

The building site of RBINS is quite large and contains a wide range buildings from the 18'th century until more recent additions in the 1980's (Figure 81). Since its heating demand is also large, the refurbishment possibilities restricted for the classified buildings and the proximity of the PHS building where geothermal test drillings were performed, the site has been deemed to be an interesting study case. The heat and cold demand profile of the site are assessed, and the feasibility is researched towards lower heating temperatures with regards to a possible geothermal heating system.

At this moment, heating the building site at low water regime temperatures is out of the question, since most of the buildings are not well insulated, some not at all, and the original radiators have been designed to be heated with steam. The last decades the buildings are heated with water up to 90-95°C during the coldest days. This is the maximum water temperatures that the gas boilers in a collective boiler room can deliver, but it is necessary so that the small radiators can give off just enough heat to compensate the losses through the uninsulated walls and leaky glass surfaces.

Firstly we focused on the high rise office building "De Vestel", where we simulated and studied one floor. Since the floors are symmetrical we could reduce the simulation work to half a floor. In the current situation we have a high heating demand (30 kW for half a floor,Figure 82 **Error! Reference source not found.**) and a lower cooling demand (max 10 kW in July, see Figure 83):

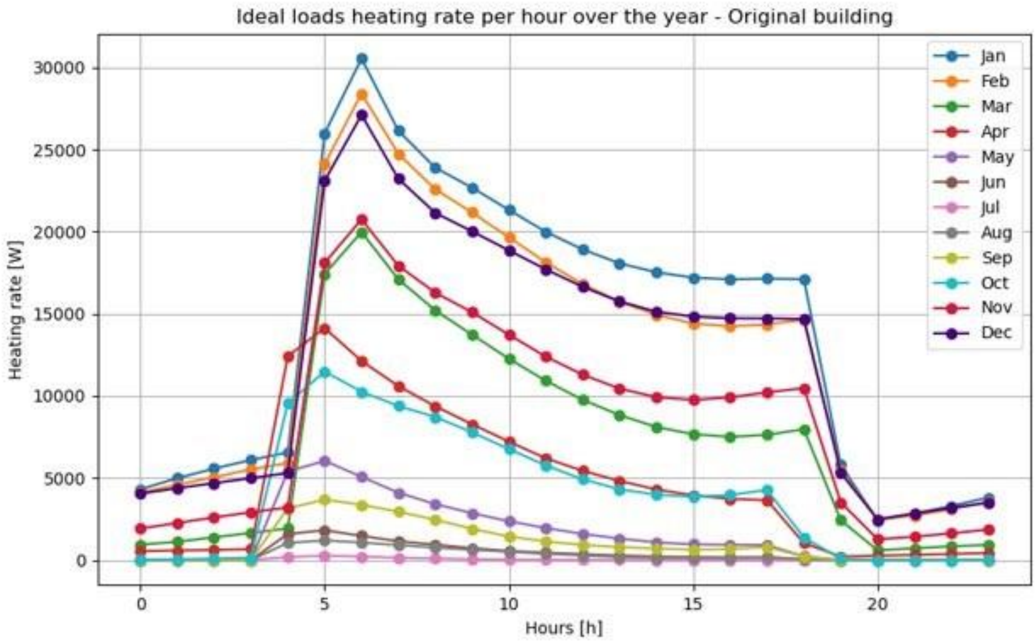


Figure 82: simulated heat load profiles for half a floor in the Vestel Tower (current situation)

The cooling demands are three times lower but in reality there is no cooling system in the most parts of the building, so people will have to use the windows to apply natural cooling, which is not always easy in high rise buildings as this one.

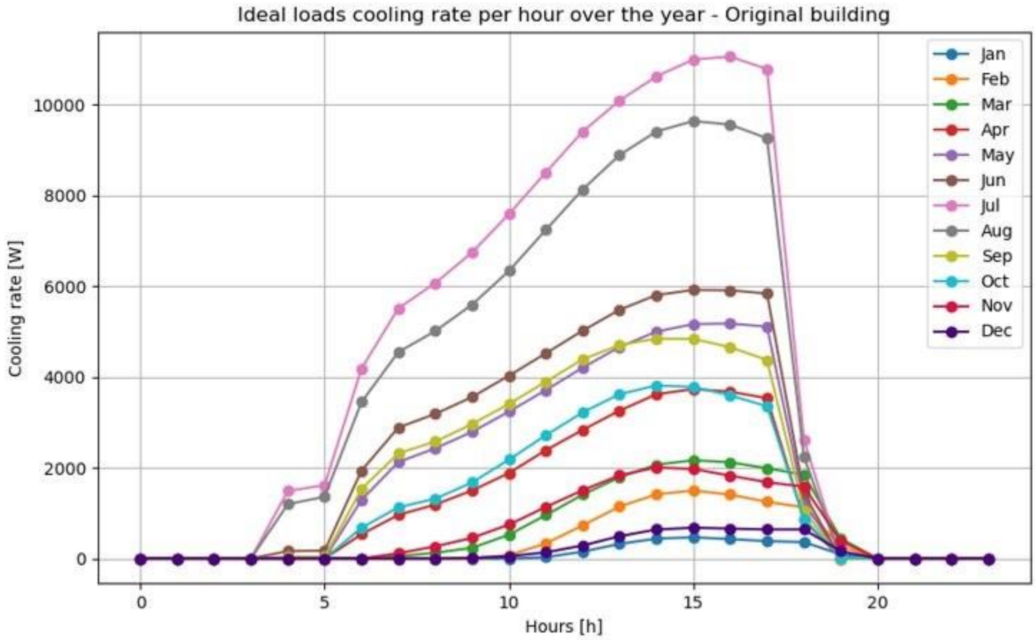


Figure 83: simulated cooling load profiles for half a floor in the Vestel Tower (current situation)

A first (temporary) measure could be a **limited renovation from the inside of these office floors**, as is already done on level 10 and 12 of the tower. This gives the opportunity to refresh the interior but also add a ventilation and climatization system so that the working environment improves. A new ventilation system following current health standards is supposed to deliver 40 m^3/h fresh air per person, which can lead up to 2000 m^3/h for the whole floor. If we preheat this air in the winter to e.g. 30°C, this would bring a large amount of extra heat into the building and is thus a great opportunity to reduce the necessary power of the radiators and also lower the radiator regime temperatures.

Calculations show that the radiators would still need about 65°C to maintain a reasonable indoor temperature at the sizing conditions of -7°C outside. However, since the building dates from the 50’s and the heating distribution pipes need to be urgently replaced, another option would be to add or enlarge the radiators so that the regime temperature can lower more. With a large heat exchanger in the air handling unit, a low working temperatures can suffice as well, so that a central regime temperature of 55°C could become possible. This would enable geothermal heat pumps to deliver the necessary heat at high efficiency. Also the necessary cooling could be delivered via the air handling units. This scenario **with a focus on a new ventilation system that enables preheating or precooling of the air and reducing the regime temperatures for heating**, could be realistic in a large part of the public buildings in Brussels. E.g. in the more recent PHS building this could be a good strategy to couple the building with geothermal heat pump systems (however taking into account that increasing ventilation levels in an existing building often demands for extra canals and can be quite intrusive).

However, in case of the Vestel, also the old skin is deteriorating fast, and so a refurbishment from the inside of the building would only be a temporary solution. Moreover, the leaky envelope could still lead to air infiltration, interferences with the ventilation system and local discomfort. A thorough restoration or even rebuilding of the envelope is a more future-proof solution.

If we would thus renovate the building, insulate the wall, replace the windows and improve the air tightness and ventilation system, the balance between heating and cooling is totally shifted: the maximum heating demand reached in January is only 3.5 kW (See Figure 84, while the cooling peaks on almost the tenfold (29 kW, Figure 85**Error! Reference source not found.**).

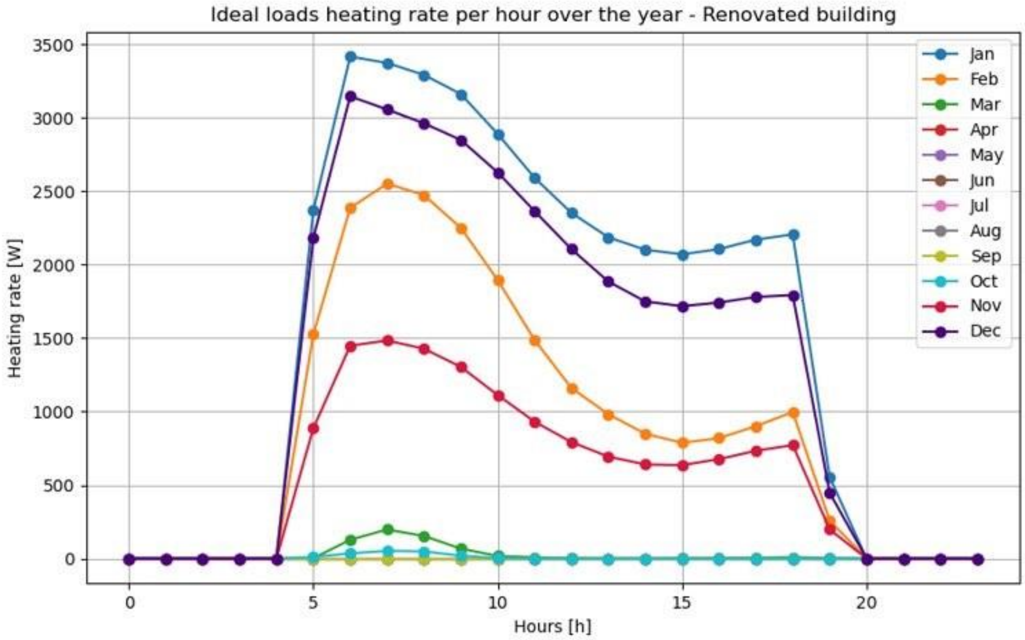


Figure 84: simulated heat load profiles for half a floor in the Vestel Tower after a thorough renovation

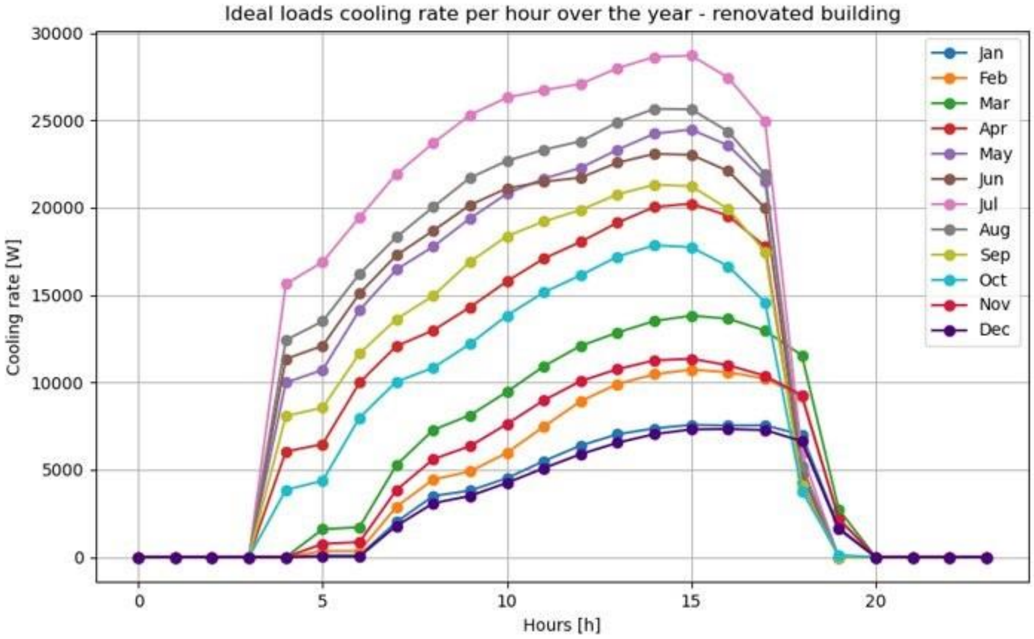


Figure 85: simulated cool load profiles for half a floor in the Vestel Tower after a thorough renovation

Applying solar shading halves the cooling needs, see Figure 86.

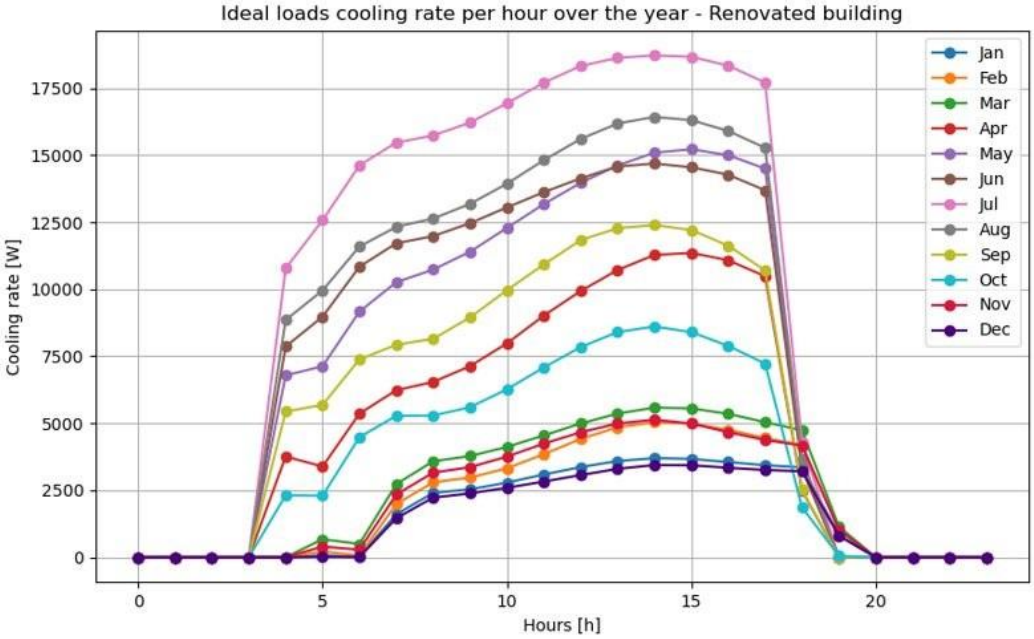


Figure 86: simulated cool load profiles for half a floor in the Vestel Tower after a thorough renovation with solar shading

Intensive ventilation schemes could reduce the cooling demand further, but it is clear that in such an office building with high internal heat gains and large window facades, cooling will probably have the largest impact on the selection and dimensioning of the systems. However, most emitter systems such as radiators, (ventilo-)convectors and also floor heating systems, can deliver more heating than cooling for the standard temperature working range. Ceiling cooling can be a good choice, since it can emit more cooling power than heating. At least this is the case if the ventilation air is also conditioned and the relative humidity is limited by dehumidification. Otherwise condensation will be formed on the coldest parts of the ceiling.

To simulate another building on the site with a very different use, we chose the museum wing “Klooster” or “Couvent” in French, the building at the center of Figure 87**Error! Reference source not found.**. This wing is already somewhat renovated in the past, with roof insulation and new windows. This is reflected on the heating demands, which are much lower compared to the “Vestel” office building.

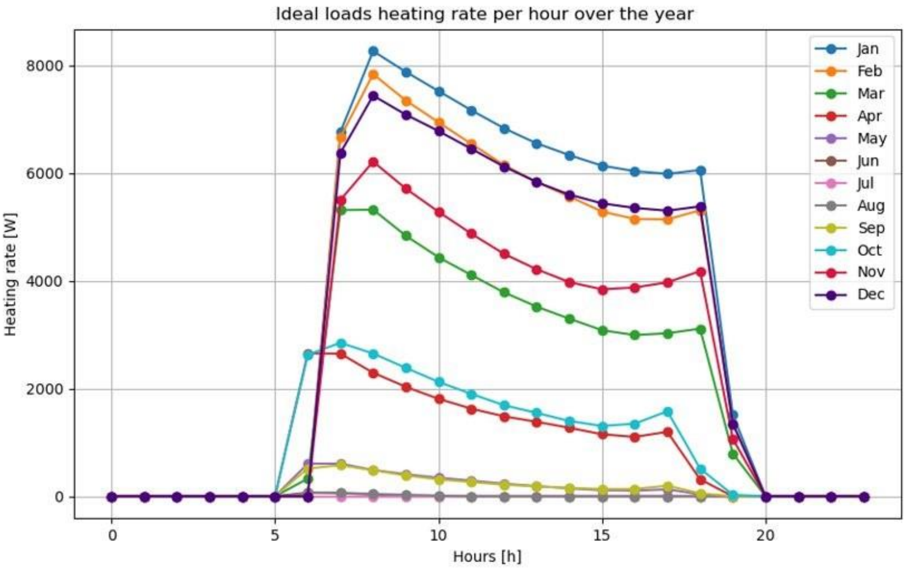


Figure 87 : simulated heat load profiles for half a museum wing (current situation, low occupancy)

The heating demand is higher than the cooling demand, simulations show a factor of about 2.5 between heating and cooling power. However, this balance is greatly influenced by the impact of the occupation rate (number of visitors present) and the connected internal heat gains. These first results are with low internal heat gains.

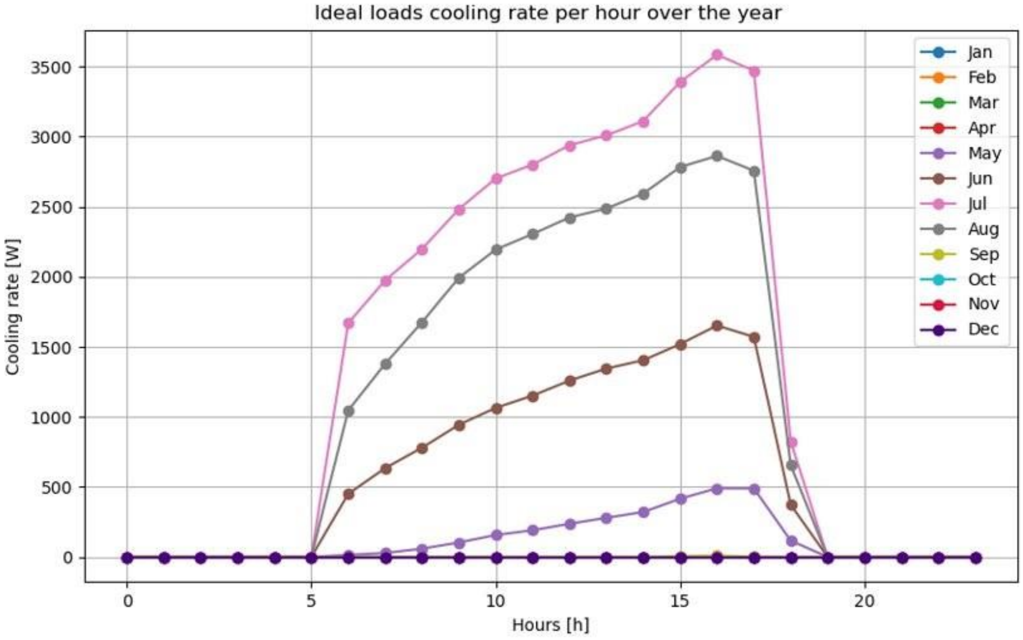


Figure 88: simulated cool load profiles for half a museum wing (current situation, low occupancy)

If we would assume more visitors and higher internal heat gains, we tend more to a balance between heating and cooling demands:

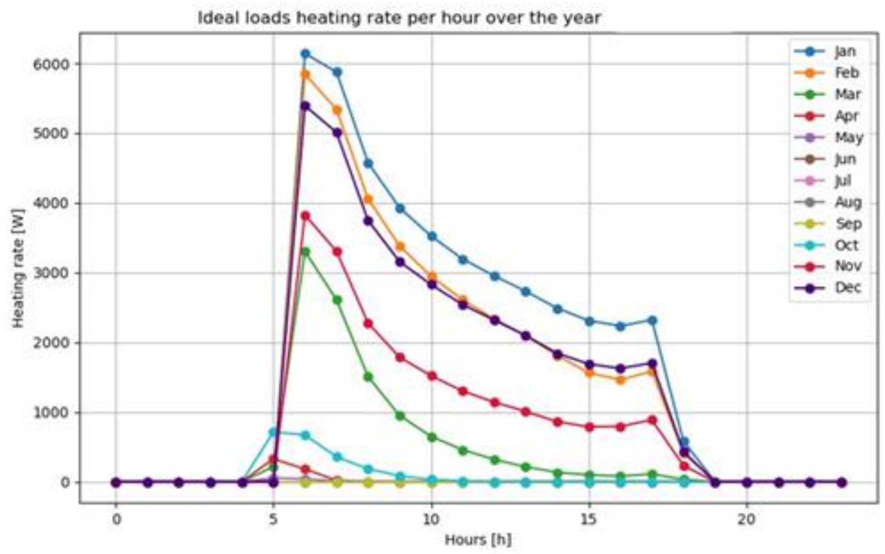


Figure 89: simulated heat load profiles for half a museum wing (current situation, high occupancy)

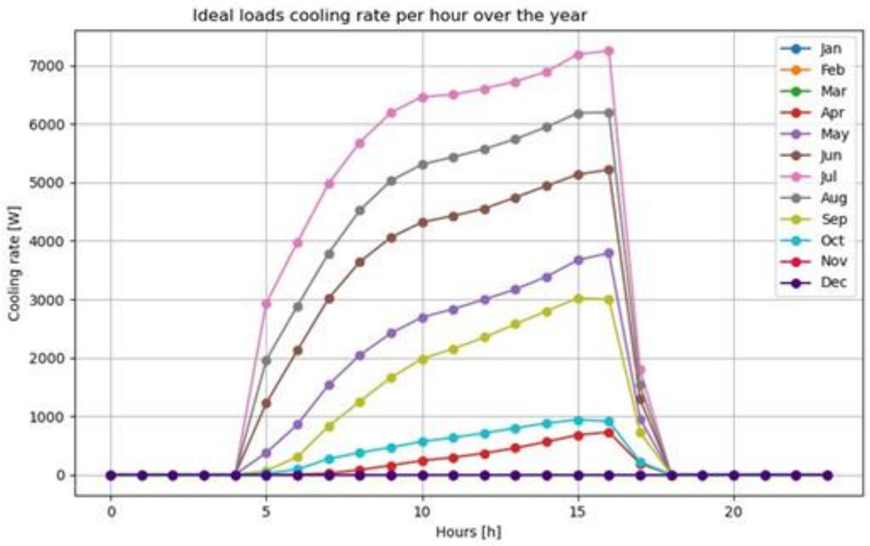


Figure 90 simulated cool load profiles for half a museum wing (current situation, high occupancy)

These results can be generalized: the simulated future energy need profiles are highly influenced by the chosen boundary conditions and assumptions that are necessary for such a dynamic energy calculation. This is even more so for better insulated buildings, since internal heat gains and solar gains have a larger impact on the heat balance there.

Regarding this museum wing, the good news is that the current air handling unit is capable of maintaining comfort here. If this AHU could be equipped with a larger heat exchanger also lower regime temperatures could be used during the heating season, so that geothermal heat pumps could be coupled and work at a higher efficiency.

If we look at the total building site, it should be possible to make all wings compatible with low temperature heating and high temperature cooling, suitable for an efficient running geothermal source and heat pump. However, as shown in above cases, it will not be easy and ask for a good mix of envelope and system measures, also taking advantage of necessary ventilation upgrades. It is thus **advised to the building owner to include geothermal energy in the retrofit feasibility study of RBINS** and take the abovementioned technical aspects into account.

4.7. Main conclusions and recommendations

The GeoCamb project demonstrated the potential of shallow geothermal energy in and around the Brussels Capital Region, specifically the potential of the deeper rock layers. It was confirmed that this potential is significant, both for closed and open geothermal systems. However, there remain important challenges and barriers, such as the techniques for drilling into hard (or weathered/fractured) rocks and the limited number of Belgian drilling companies skilled in this technique. The project also demonstrated that geophysical measurements using the HVSR technique are able to determine the depth to the bedrock, which is a cheap solution for companies to improve bedrock knowledge prior to drilling. However, only with advanced geophysical array techniques the weathered part of the bedrock can be identified as the HVSR technique proved to be only useful as detective tool for finding the soft sediment – bedrock contact. The project helped reduce uncertainties regarding the precise depth and nature of the rock layers, although a certain level of risk and a (limited) chance of failure still exist.

The case studies illustrate the functioning of both closed and open geothermal systems. These case studies further emphasized the importance of proper monitoring of a geothermal system to ensure optimal performance. Comprehensive monitoring and thorough follow-up by experts are crucial in this regard.

In addition, the renovation case studies demonstrated that shallow geothermal energy can also be applied in older large-scale buildings, provided that sufficient measures are taken to limit the energy demand and peak powers. These peaks will have an influence on the dimensioning of the geothermal source but also determine the necessary emitting power of heating and cooling inside the buildings. E.g. reducing the heat demand by insulation and ventilation measures will lower the (peak) demand and facilitate the use of lower water temperatures in the existing heating systems, so that the geothermal system with its heat pumps can maintain a high efficiency.

However, both the cases of RBINS-PHS and the apartment blocks also showed the risk of boosting the cooling demands. If the envelope is insulated and no efforts are made to reduce solar gains (screens, specific glazing, …) or evacuate internal heat gains (extra ventilation), then large cooling needs can be expected. This can cause overheating in the building when the emitters cannot reach the necessary cooling capacities and/or lead to an imbalance in the geothermal source and problems in the long run.

So by applying less or more passive cooling measures (solar shading, screens, ventilative cooling, …) the balance between heating and cooling needs can be refound. Often this can lead to extra investment costs in building, but savings on the long run, since it has a positive impact on the design and overall cost of the geothermal system (see the Molenbeek case study in chapter 4.2).

If the balance between yearly heating and cooling demands is not feasible for the building (by applying envelope measures), extra buildings in the neighbourhood could be connected on the geothermal source to compensate for the imbalance (eg. A building with high heating demand, very low cooling demand). A last technical solution for the imbalance problem, and a possible solution to rectify a faulty design, is the addition of an air heat exchanger (dry cooler, cooling tower, …), so we get a hybrid heat pump system that is able to dump the heat surplus in the air (or vice versa) so that the balance in the ground can be maintained. This shows that there are multiple solutions to heat and cool buildings with geothermal energy, but the design of the building, its technical systems, and the geothermal system should be coordinated throughout the design process to achieve an optimal, cost-efficient solution.

Important efforts still need to be done in the coming years for further market development by overcoming key barriers, including high investment costs, insufficient financial support, system performance uncertainties, policy gaps, and low public awareness. Achieving Belgium's ambitious renewable energy targets for 2030 will require a substantial expansion of geothermal energy use alongside other renewable sources.

5. DISSEMINATION AND VALORISATION

5.1. Communication strategy (FINN)

The GeoCamb project intended to invest significant time and resources in raising public awareness and promoting the importance of federal funded projects to society, as well as to ensure that potential stakeholders and policy makers follow up progress and benefit from the GeoCamb results.

In order to achieve these objectives the FINN communication agency was selected (tender procedure) to support the GeoCamb team to define a project communication strategy. FINN has organized a workshop with the partners. During this session three key aspects were tackled: stakeholders, issues & messages. Following this workshop, FINN analysed the input and translated into a communication strategy report (available in Annex 3).

5.2. GeoCamb dissemination

The Geocamb project has leveraged diverse communication strategies and stakeholder engagement activities to promote its findings and objectives (see the lists and references in chapter 6). Presentations and workshops at international conferences, such as the European Geothermal Congress (2022), the Geologica Belgica Conference (2021 & 2024), the IAH Congress (2021 & 2024), and various EGU and AGU conferences have showcased the project's multidisciplinary approach and highlighted its role in advancing geothermal energy research. By participating in sector-specific events like the “Learning Network on Geothermal Energy,” we targeted industry stakeholders, providing practical insights about geothermal potential in Cambrian basement.

Site visits such as the one at the Paul-Henri Spaak building (2021), fostered direct interaction with geological community, emphasizing project applications in public buildings.

Public engagement initiatives, including training courses (Geothermal Energy in Wallonia, IFAPME (Embuild)) and events like "Saviez-vous" or conference at “Cercle d’Histoire de Bruxelles “ (2023), as the Press conference on the Molenbeek-Gandhi drilling site, ensured outreach to broader audiences, raising awareness of geothermal energy's potential. Student trainings with data acquired in the course of GeoCamb furthermore gives visibility and awareness to the young generation.

Moreover, collaboration with federal institutions was spotlighted in invited talks, such as the 125th Anniversary of the Geological Survey of Belgium (2022). This comprehensive approach has enabled the dissemination of scientific knowledge, strengthened partnerships with policymakers, and contributed to the project's legacy in promoting sustainable energy solutions in Belgium and beyond (see the list of events in 6.3).

5.3. Valorisation

Screening tool

A simplified version of the BHE design methodology developed and used by ULB (analytical model for BHE design) was integrated into the Buildwise geothermal screening tool (https://tool.smartgeotherm.be). This significantly increased the accuracy and reliability of the BHE screening of the tool. This work was finished in the beginning of 2025. This tool was originally created during the Smart Geotherm project (Vlaio) and further improved via internal Buildwise funds and the Brugeo project (EFRO-FEDER - BXL). The tool is used by a lot of drillers, contractors and building owners when preparing their geothermal project.

Benchmarking ROB ambient noise approaches in various international collaborations

The conducted work in the geophysical part of GeoCamb has allowed automating a lot of geophysical analysis procedures. These procedures include the automatic analysis of ambient noise measurements, automatic picking of f0, automatic profile imaging and interpolatation. This improvement was valorised in several international collaborations where the ROB was asked to apply the developed procedures during GeoCamb on various geological questions. Here below a short overview of different initiatives

- In October 2022, Koen Van Noten and Martin Zeckra (ROB) were invited by seismologists of the Bundesanstralt für Geowissenschaften und Rohstoffe (BGR) to a field survey in Hamelin (DE) at a BGR site of interest. At this site, paleoterraces of the Weser River show a changing thickness below a - now inactive – nuclear power plant. Ambient noise nodal array and HVSR techniques were applied to characterise the subsurface of the site. The road book on how to use the ROB’s seismic nodes was applied to maximise measuring time over installation time. The results were very promising and support the hypothesis of thickening river terraces over a fault structure running below the power plant. These kinds of collaborative works show the strength of expertise gained during Brain projects.
- In December 2022, November 2023 and October 2024, the ROB organised UlB geophysical student field courses in the region of Halle, Uccle and Etterbeek. All the acquired data has been integrated in the HVSR database.

- In February 2023, Koen Van Noten, Thomas Lecocq and Raphael De Plaen participated to the 23th Skience Winter school in Münich. During this winterschool training, we thought participants how to process HSVR data manually and automatically and how to create bedrock cross-profiles. The dataset that was used was the 2022 Tour & Taxis HVSR dataset gathered in the course of the GeoCamb Project. The data, codes and results are available on Github.
- In January 2024, the ROB was asked by the Vlaamse Waterweg to perform a geophysical exploration campaign around the Bospoortbrug (Halle), which is currently being renewed. By installing seismic sensors around the bridge, HVSR was applied, and bedrock depth was derived and modelled. GeoCamb procedures were followed and the resulting virtual borehole data is being used by the engineering planning team.
- In April 2024, Koen Van Noten and Thomas Lecocq (ROB) led a geophysical campaign below the University of Lille (France) to create several bedrock depth profiles below the university as there is a strong interest in exploring the Carboniferous below that campus. In 2 days, 101 datapoints in 401h of data was recorded. An internship student currently applies the tools developed during GeoCamb.

6. PUBLICATIONS

6.1. Peer-reviewed publications

- Manon Bulté, Thierry Duren, Olivier Bouhon, Estelle Petitclerc, Mathieu Agniel, Alain Dassargues. **2021**. Numerical Modeling of the Interference of Thermally Unbalanced Aquifer Thermal Energy Storage Systems in Brussels (Belgium). Energies 2021, 14, 6241. https://doi.org/10.3390/en14196241
- Van Noten, K., Lecocq, T., Goffin, C., Meyvis, B., Molron, J., Debacker, T. N. and Devleeschouwer X. **2022**. Brussels' bedrock paleorelief from borehole-controlled power laws linking polarised H/ V resonance frequencies and sediment thickness, J Seismol, 26, (2022), 35–55. DOI: https://doi.org/10.1007/s10950-021-10039-8
- Zeckra, M., Van Noten, K., Rapagnani, G., Lecocq, T., **2022**. "Sensitivity, Accuracy and Limits of the Lightweight Three-Component SmartSolo Geophone Sensor (5 Hz) for Seismological Applications" Paper submitted to Seismica: https://eartharxiv.org/repository/view/3564/
- De Paoli, C., Duren,T., Petitclerc, E., Agniel, M., Dassargues, A., **2023**. Modelling Interactions between Three Aquifer Thermal Energy Storage (ATES) Systems in Brussels (Belgium). Appl. Sci. 2023, 13, 2934. https://doi.org/10.3390/app13052934

6.2. Other papers and articles

- Van Noten, K., De Plaen, R., "Bepaling van de sokkeldiepte van het Brabant Massief met behulp van seismische ruismetingen ter hoogte van de Bospoortbrug te Halle" Expertiserapport ROB-DVW 2024-01. Koninklijke Sterrenwacht van België, Ukkel. pp. 34 (2024). https://doi.org/10.24414/4539-0k37
- Techlink, "Geothermisch potentieel voor publieke gebouwen in Cambrische sokkel" Techlink magazine Heat+, p.48-50, November 2024.

6.3. Presentations at conferences and symposia

- Van Noten, K. et al. **2020**. ‘Creating a harmonised HVSR database for Belgium’. *Rhine-Meuse Seismology international meeting* (online).
- Petitclerc, E. et al. **2020**. ‘Why and how does Shallow Geothermal Energy (SGE) work at Brussels ?’ European Shallow Geothermal Days 2020 (online conference). Youtube
- Van Lysebetten, G., Van der Veken, J. **2020**. ‘Geothermal screening tool’. Participation to session 1 of the ‘Learning Network on Geothermal Energy’ on the BBRI/Smart Geotherm geothermal screening tool, organized by the Flemish Construction Confederation (Vlaamse Confederatie Bouw or VCB) and funded by VLAIO.
- Petitclerc, E. **2021**. ‘GEOCAMB project, scope and objectives’ Site visit at the Paul-Henri Spaak building of the European Parliament by members of the Belgian and Luxembourg Union of Geologists
- Van Lysebetten, G., Van der Veken, J. **2021**. ‘BBRI Technical note TVN/NIT259 on the “Design and execution of closed geothermal systems with U loop heat exchangers”’. Participation to session 2 of the ‘Learning Network on Geothermal Energy’ on geothermal design, organized by the Flemish Construction Confederation (Vlaamse Confederatie Bouw or VCB) and funded by VLAIO.
- BBRI partners. **2021**. ‘Lerend Netwerk Geothermie’ organised by the Flemish Construction Federation (VCB), presentations by Jeroen Van der Veken and Gust Van Lysebetten.
- Petitclerc, E. et al. **2021**. ‘The GeoCamb Project’ 7th International Geologica Belgica Meeting at the Africa Museum Tervuren (Belgium)
- Petitclerc, E. et al. **2021.** “New geological, hydrogeological and geothermal insights into the potential of the Cambrian basement for geothermal energy in Brussels, Belgium”, oral presentation at 48th IAH Congress.
- Van Lysebetten , G. **2022**. Oral presentation ‘Lerend Netwerk Geothermie Beginners’ organised by the Flemish Construction Federation (VCB).
- Van Noten, K., **2022**. "When Federal Scientific Institutions (FSIs) join forces" (2022). Invited talk presented at 125th Anniversary of the Geological Survey of Belgium on 2022-06-09.
- Van Noten, K., Zeckra, M. **2022** "Bedrock depth characterisation below public buildings with a geothermal interest using ambient seismic noise". Talk presented at 3rd European conference on earthquake engineering and seismology on 2022-09-08 by M. Zeckra.
- Baudinet, C., Van Noten, K., Zeckra, M., Van Breusegem, M., Van Lysebetten, G., Van der Veken, J., Walraevens, K., Van Camp, M., Petitclerc, E. **2022** "Multidisciplinary approach to assess the Cambrian geothermal potential in Brussels region with a focus on public buildings (GeoCamb project)" (2022). Talk presented at European Geothermal Congress 2022 Berlin, Germany on 2022-10-19 by E. Petitclerc.
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- Van Noten, K., Zeckra, M., Lecocq, T., De Plaen, R., Govoorts, J., Hobiger, M., Igel, H. **2023.** Performance of SmartSolo Seismic Nodes for Seismological, Environmental and Shallow Geothermal research. Poster presented at AGU23, San Francisco , USA, 11-15 December 2023.
- Petitclerc, E. February **2024**: “Geothermal Energy in Belgium”, Poster at Belgian Climate Center conference, T&T, Brussels.
- Petitclerc, E. ,26th of June **2024**: “Brussels geothermal potential” Oral Presentation at meeting of Natural History Museums directors of the world (G13), Brussels.
- Orban, P. , De Paoli , C., Agniel, M., Petitclerc, E., Duren, T., Peret, J., Dassargues, A., **2024**. ‘Five adjacent Aquifer Thermal Energy Storage (ATES) systems in Cenozoic and Palaeozoic aquifers in Brussels: numerical simulation of their possible interactions’, talk presented at Geologica Belgica Luxemburga International Meeting 2024, Liège, Belgium.
- Walraevens, K., Yenehun, A., Van Camp, M., **2024.** ‘Pumping tests and hydrogeological characteristics of the Cambrian aquifer in the Belgian Brabant provinces for geothermal potential’. Poster presented at Geologica Belgica Luxemburga International Meeting 2024, Liège, Belgium
- Van Noten, K., Zeckra, M., Deplaen, R., Lecocq, T., Govoorts, J., **2024**. "Performance of SmartSolo Seismic Nodes in Seismological, Environmental and Geophysical research". Poster presented at British Seismology Meeting, Reading, UK.
- Van Noten, K., De Plaen, R., Lecocq, T., Zeckra, M., "Nodal urban seismology for society" **2024**. Talk presented at ESC2024, Corfu, Greece on 2024-09-26
- Van Noten, K., Scherps, E., De Clercq, E., Zeckra, M., De Plaen, R., Vanneste, K., Govoorts, J., Lecocq, T., **2024**. "A geophysical database for Belgium". Talk presented at Geologica Belgica Luxemburga International Meeting 2024, Liège, Belgium on 2024-09-12.
- Yenehun A., Van Camp M., Walraevens K. Pumping tests and hydrogeological characteristics of the Cambrian aquifer in the Belgian Brabant provinces for geothermal potential at 8th International Geologica Belgica Luxemburga Meeting 2024, held at Liège (Belgium) from 11-14 September **2024** (poster).

The Geocamb and Designate Final conference took place at RBINS on 16th of September 2024 and gathered about 60 people.

6.4. Thesis, internships and trainings

- Boulard, C. 2022. "H/V spectral ratio analysis in urban areas interested in shallow geothermal wells". UlB MSc thesis. Promoters: K. Van Noten (ROB and M. Zeckra (ROB)
- Gauthier, A. 2022. UCL-Ecole Polytechnique – Stage en entreprise (EPL) – Master Ingénieur civil des construction- Promotors : Gust Van Lysbetten (Buildwise), co-promotor: Estelle Petitclerc (GSB)
- Massant, A. 2021. « Étude de forages géothermiques au Parlement Européen et à Anderlecht dans le cadre du projet GEOCAMB ». ULB stage en entreprise_ Master Ingenieur civil construction. Promotors : Estelle Petitclerc (GSB) & Nadine Mattielli (ULB)
- Petitclerc, E., Van Breusegem, M., 22nd March **2024**. “La géothermie en Wallonie”, oral presentations for the Shallow geothermal training day for professionals organised by Embuild, Centre IFAPME des Isnes, Wallonia.
- Scherps, E. 2021. Developing a HVSR database for Belgium. Internship at the Seismology-Gravimetry section of the Royal Observatory of Belgium. Internship report. Katholieke Universiteit Leuven, MSc Geography. Promoters: K. Van Noten (ROB), Prof. dr. M. Kervyn (VUB)
- Van Noten, K. 2023. HVSR training at the 14th Skience Munich winter school using GeoCamb data

6.5. Support to decision making

- 26/10/2020. Estelle Petitclerc, RBINS-GSB. Presentation of the on-going geothermal projects at the GSB to the Cabinet of State Secretary Thomas Dermine
- January 2022. Estelle Petitclerc, RBINS-GSB. Presentation of Geothermal energy perspectives for Wallonia to the Walloon Energy Ministry cabinet.
- 2023-2024. Gust Van Lysebetten (Buildwise). Follow-up and advice on the project “Uitbouw ondiepe geothermie in Vlaanderen” of the Flemish Government (Environmental Department) through the steering committee.

6.6. Press and media interviews

A press conference took place on the Molenbeek-Gandhi drilling site the 17th of October 2022. About 10 journalists participated to the site visit. Koen Van Noten (ROB), Jeroen Van der Vekken (Buildwise), Camille Baudinet and Estelle Petitclerc (SGB) presented the case-study and replied to journalists.
The following articles in newspapers and reportage/interviews on TV were released:

- Le Soir Bruxelles: “Un puits de 150m pour mieux comprendre le sous-sol de Bruxelles », 2 pages, 17/10/22.
- La Capitale, Sudinfo : « De l’energie géothermique pour chauffer les logements sociaux », 1 page, 21/10/22.
- La Libre Belgique Bruxelles : « La géothermie à la rescousse de Bruxelles », 1 page, 21/10/22.
- Van Noten, K., Baudinet, C., Agniel, M. 2022. "Puiser la chaleur de la terre pour chauffer et refroidir les bâtiments: la géothermie, une solution verte et économique ?". RTBF Journal 19h30 on 2022-10-19.

- Van Noten, K., Baudinet, C. 2022. "Gezocht: aardwarmte in de diepe ondergrond van Brussel". De Standaard (Pascal Sertyn) on 2022-10-19
- Van der Veken, J., 2022. “Geothermische verkenningsboringen in Molenbeek”. VRT journaal 10h on 2022-10-20.

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8. ACKNOWLEDGEMENTS

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ANNEXES

Annex 1 Report on Molenbeek-Gandhi drilling, e-TRT and geophysical logging (in French)

Annex 2 Hydrogeological simulation of the interactions of five adjacent Aquifer Thermal Energy Storage (ATES) systems in the Cenozoic and the Cambrian aquifers in Brussels (Belgium)_ September 2024

Annex 3 Geocamb communication strategy (FINN)